Lecture 26

Origin of the Solar System

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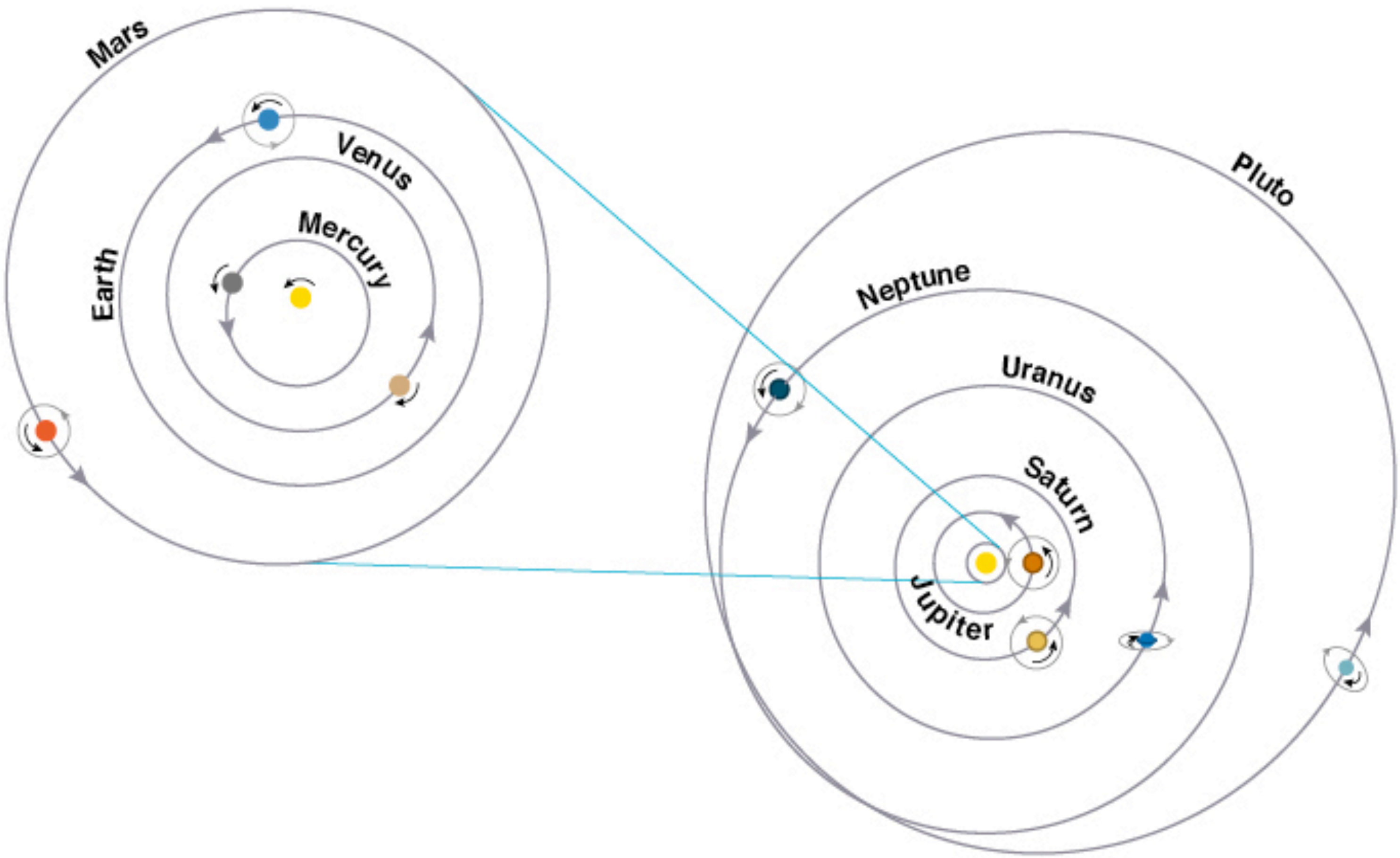
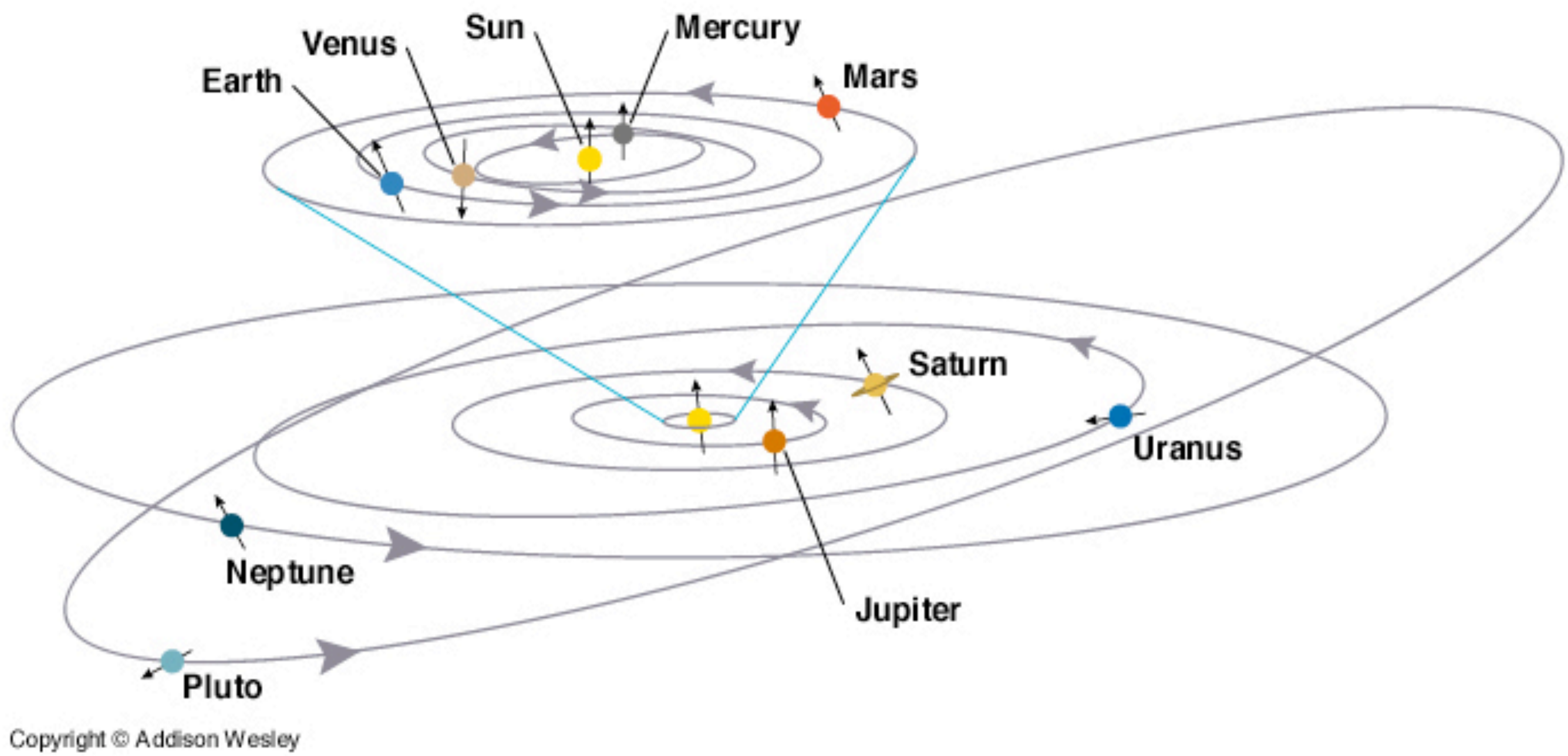
- Nebular Hypothesis:
  - Laplace's version and its problems
  - Modern version: accretion disk with inward transport of mass and outward transport of angular momentum
- Star Formation:
  - Condensation of molecular cloud cores
  - Gravitational instability and infall to form star + disk
  - Bipolar outflow stage
  - T Tauri stars and protoplanetary disks
- Planet Formation:
  - Planetesimal formation: icy = comets, rocky = asteroids
  - Gravitational aggregation, focusing, and runaway growth
  - Isolation at lunar sizes and larger
  - Growth to planets:
    - Terrestrial planets by large impacts at late stages
    - Giant planets by reaching critical core mass followed by rapid accretion of gas in the case of Jupiter and Saturn.
  - Extrasolar planets -- evidence for orbit migration
  - Role of late impacts in evolution of life on Earth

Planets Revolve in Mostly Circular Orbits in Same Direction as Sun Spins

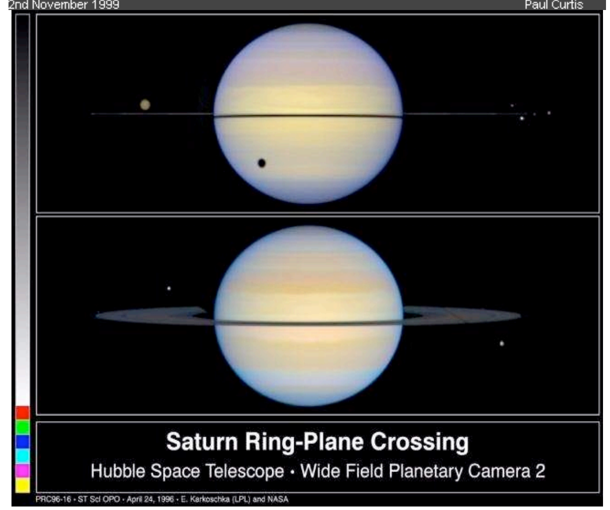


Planetary Orbits Nearly Lie in a Single Plane with Exception of Pluto & Mercury



Jupiter and Saturn as Miniature Solar Systems

- Huygens (1629-1695) points out that four Galilean satellites revolve around Jupiter in the same sense as Jupiter spins about its axis (as measured by rotation of Great Red Spot in 1665 by Cassini), as well as satisfy their version of Kepler's third law. The system resembles therefore a miniature solar system.
- Huygens also explains geometry of Rings of Saturn.
- Drawing an analogy with Saturn and its rings, Laplace (1749-1827) proposes nebular hypothesis for the origin of the solar system.



Rise and Fall of Original Nebular Hypothesis

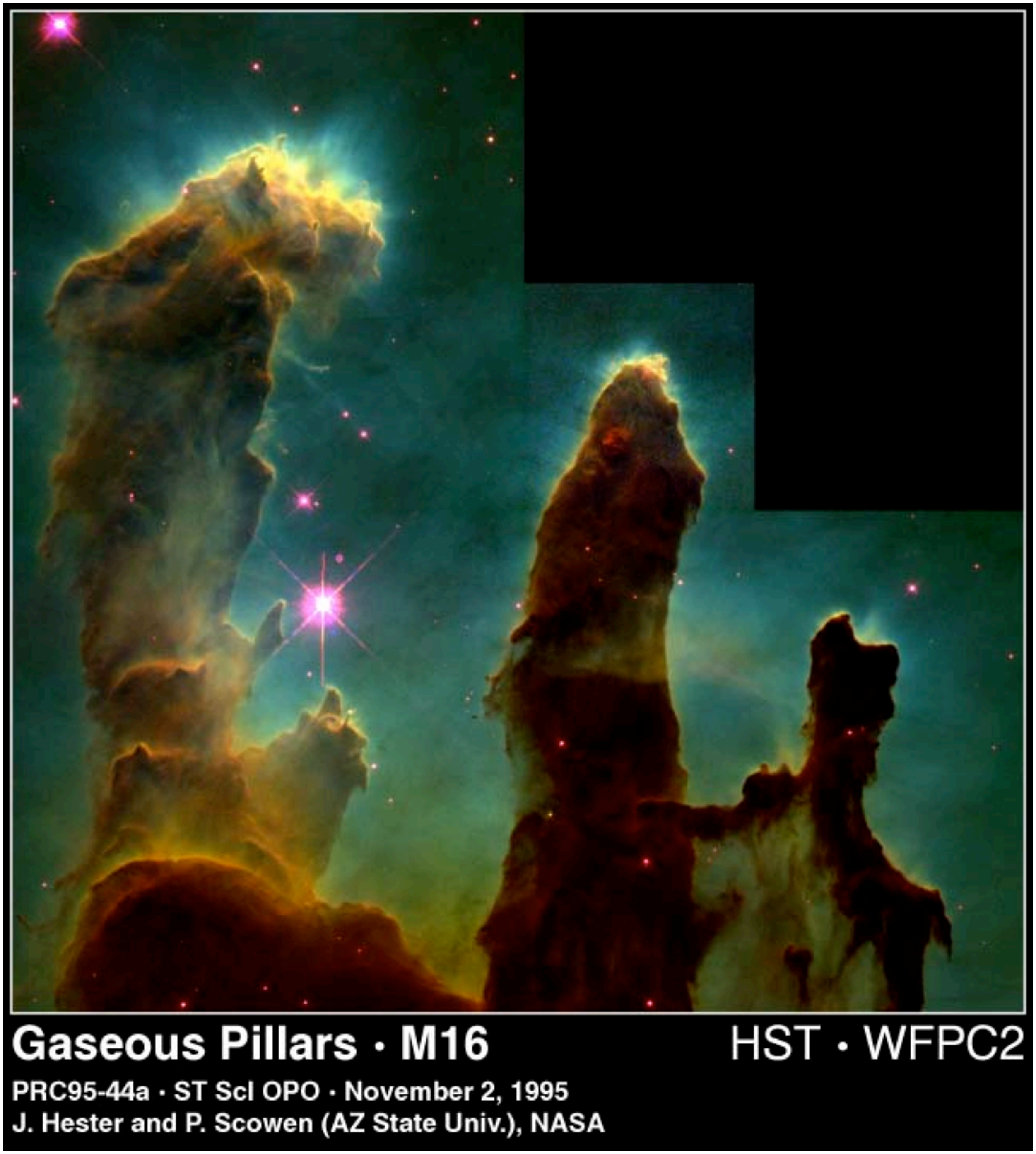
Pierre Laplace (1749-1827):

- Sun begins as large spinning body.
- As Sun contracts, it spins faster until it becomes oblate (like Saturn) and begins to shed successive rings of material that becomes a disk (not how Saturn did it).
- As Sun continues to contract, and source of light and heat recedes from rings, the matter in the disk cools and cogeals into solids.
- Solids accumulate over time to become planets.
- This scenario then explains why planets all orbit in the same direction as the Sun spins and in a single plane corresponding to the equatorial plane of the Sun.

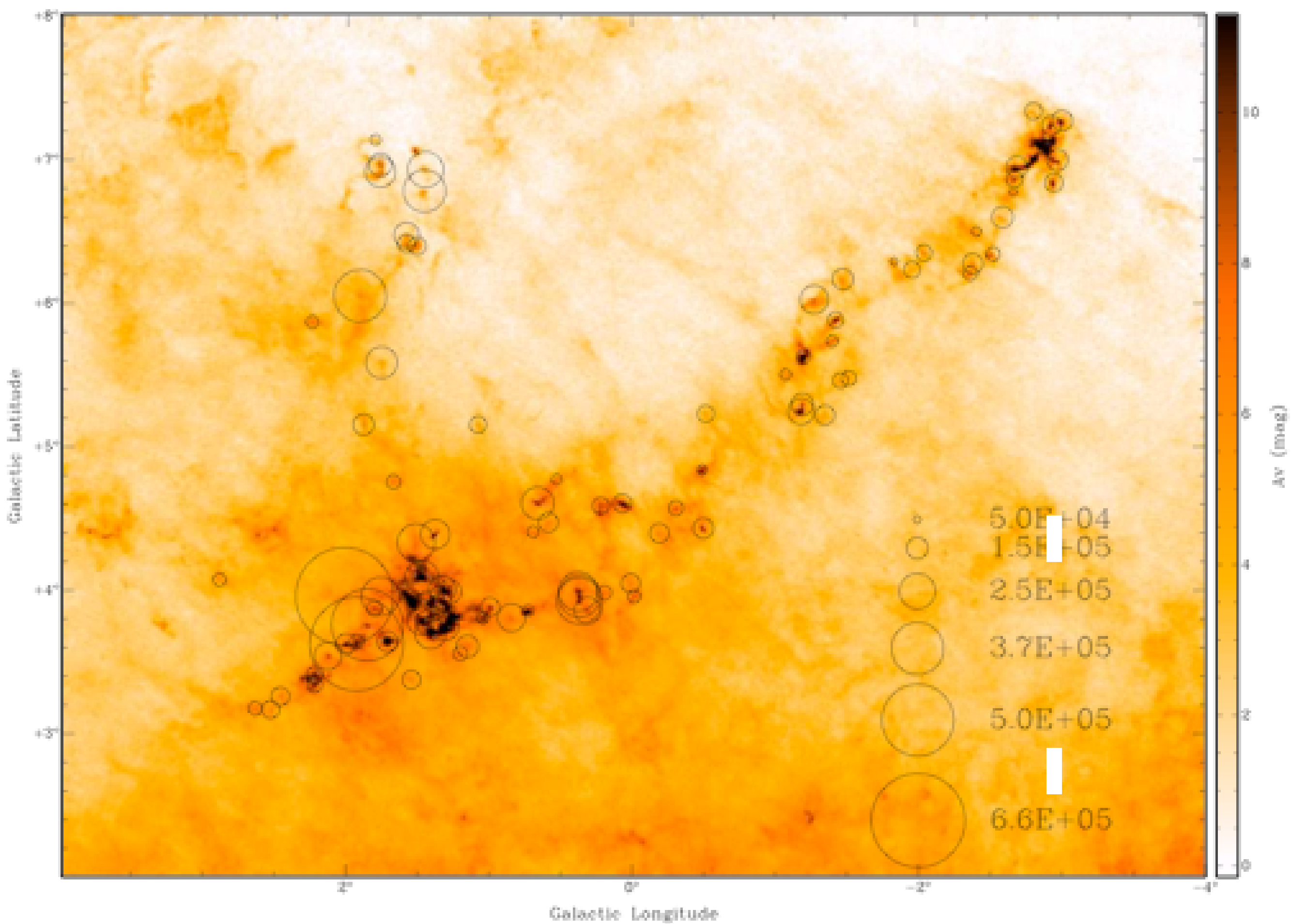
George Darwin (1845-1912):

- Sun has 99.9% of the mass of the solar system, but only 2% of the angular momentum.
- Jupiter and Saturn contain in orbital angular momentum the bulk of the rest.
- If one were to expand the Sun (backwards in time) to the size of Jupiter and Saturn and allowed it absorb the angular momentum of these planets, the protosun would have rotated well below “break-up” (because of its large mass). It would not have shed rings a la Laplace.
- These devastating arguments spelled death knell for “nebular hypothesis” until resurrected in recent times by modern theories of the star formation process.

Low-Mass Star Formation Occurs in Rotating, Dense, Magnetized Cores of Turbulent, Dark Molecular Clouds.



Cloud Cores in Pipe Nebula

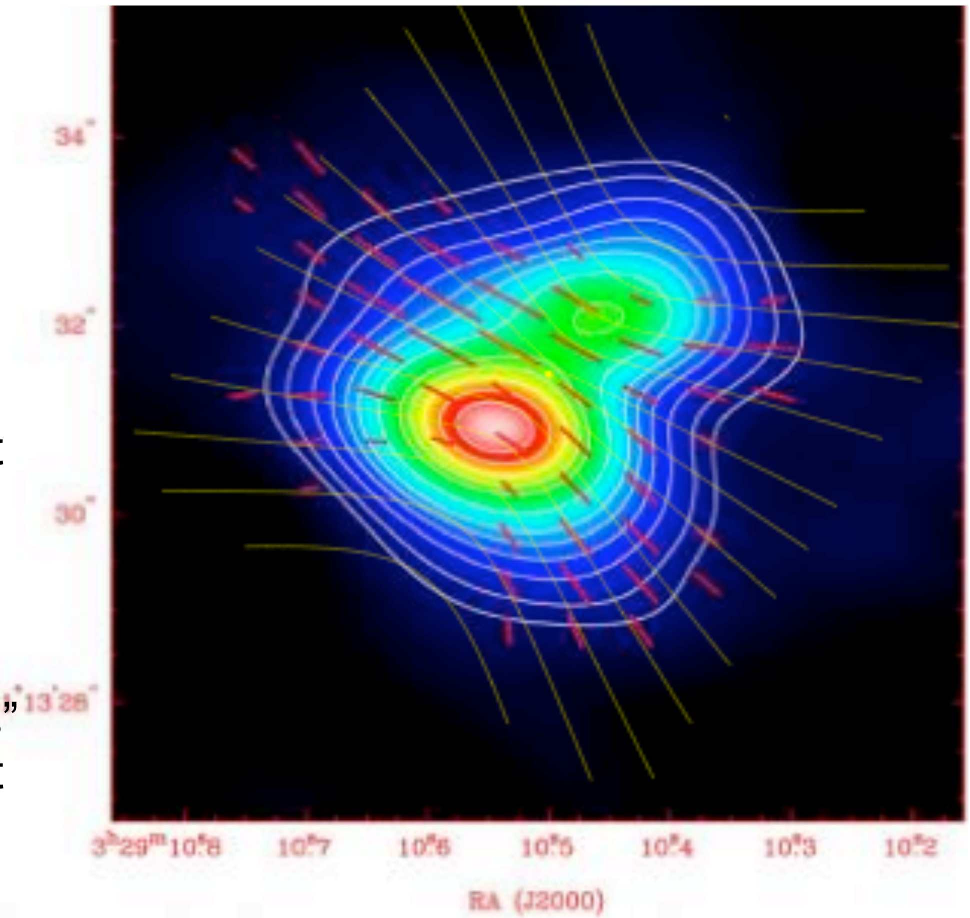


Dense cores of gas and dust that are the future sites for the appearance of new low-mass stars and planetary systems form as they slip past the magnetic fields that help support them against their self-gravity.

Lada, Muench, Rathborne, Alves, & Lombardi (2007))

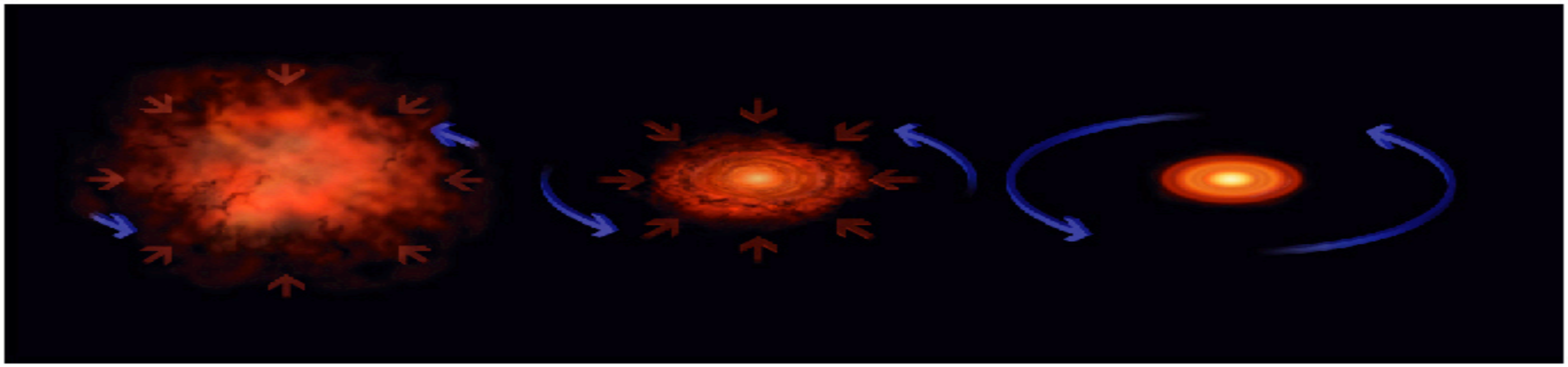
Rotating, Resistive Collapse Produces Magnetized Star + Disk

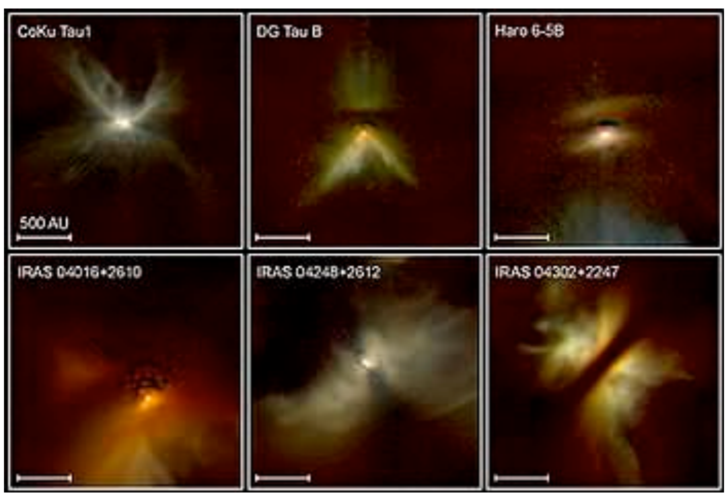
- Red dashed lines = measured directions of magnetic fields.
- White lines = best theoretical fit.
- Conclusion: magnetic fields brought into disks are about 1/2 as strong as if fields were frozen to the matter during the collapse.
- Fields are still strong enough to make disks magnetically “viscous” (MRI), leading to inward transport of mass and outward transport of angular momentum.

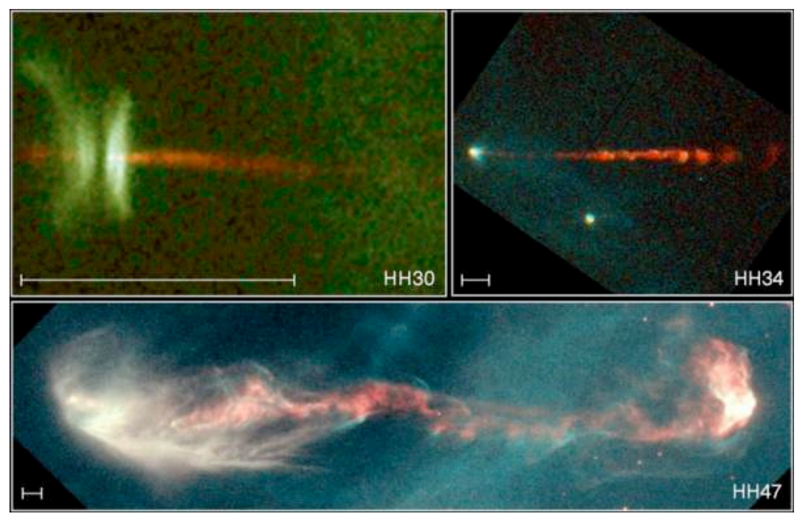


Girart et al. (2006); Gonzalez et al. (2007)

Formation of New Star Surrounded by a Protoplanetary Disk







Disks from young stellar objects are frequently accompanied by jets and outflows.

X-Wind Model of Protostellar Outflows

Viscous processes, involving magnetic fields dragged in from interstellar space, transports angular momentum outward and matter inward, accounting for strange distribution where Sun has 99.9% of the mass, but the planets (particularly Jupiter and Saturn) have all but 2% of the angular momentum.

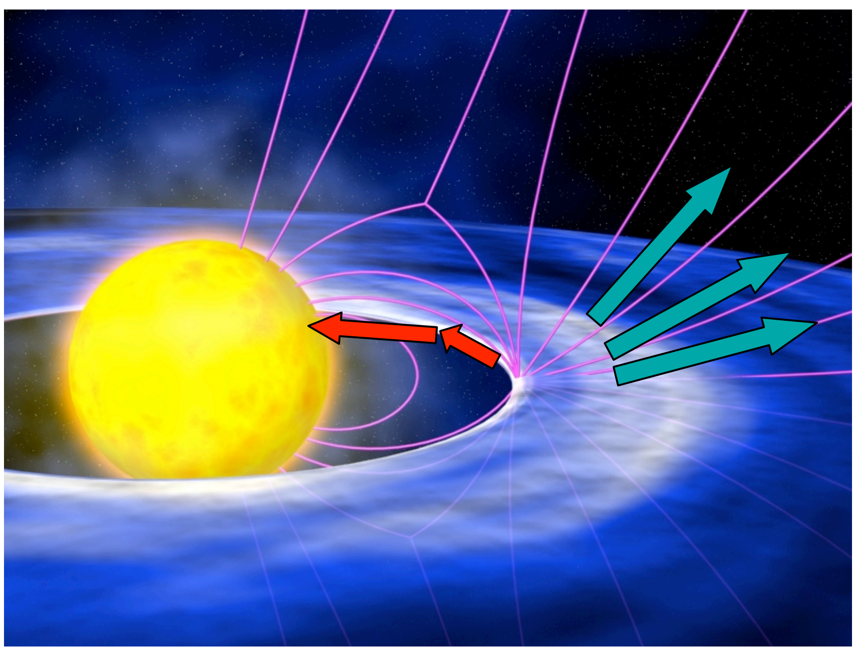
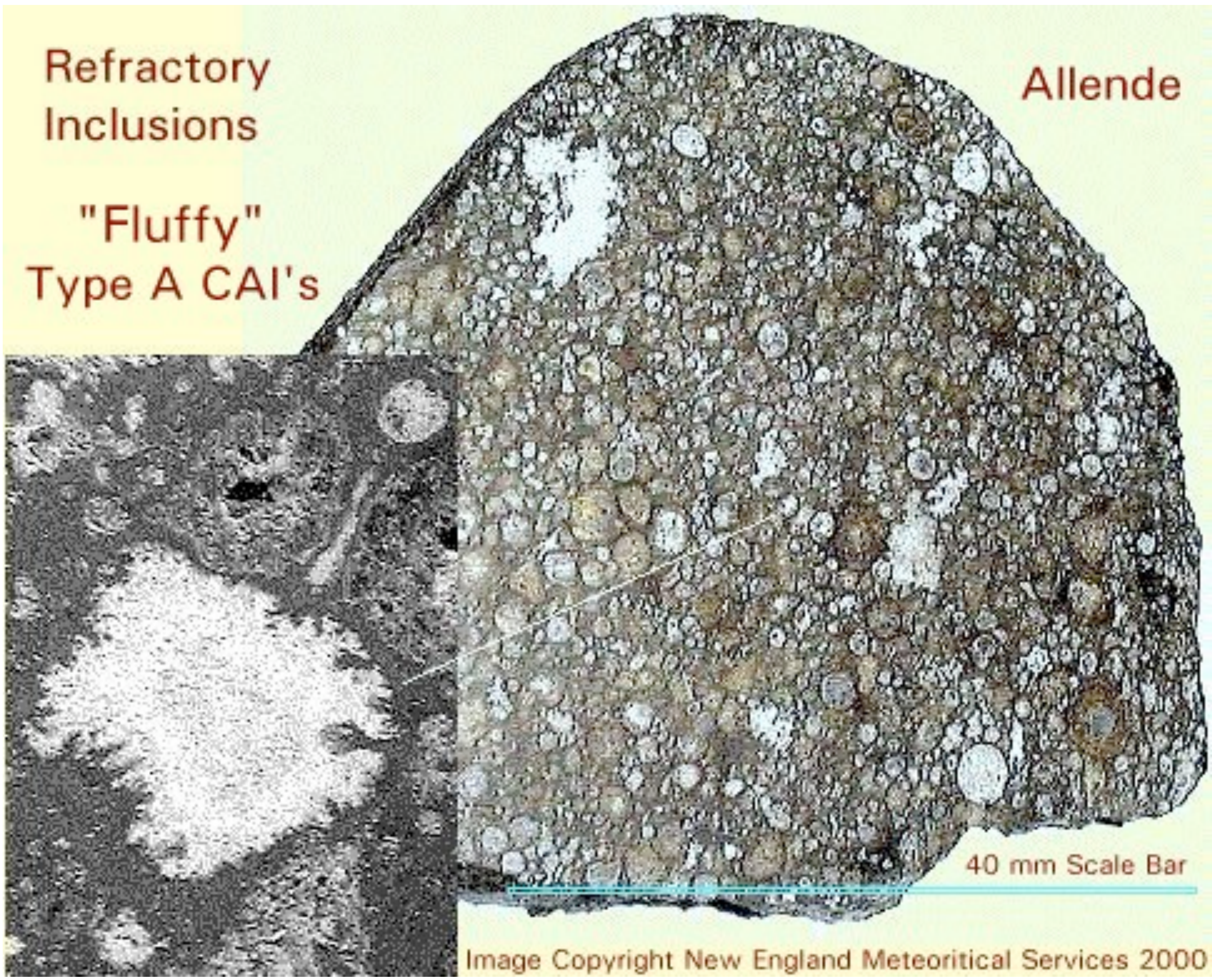


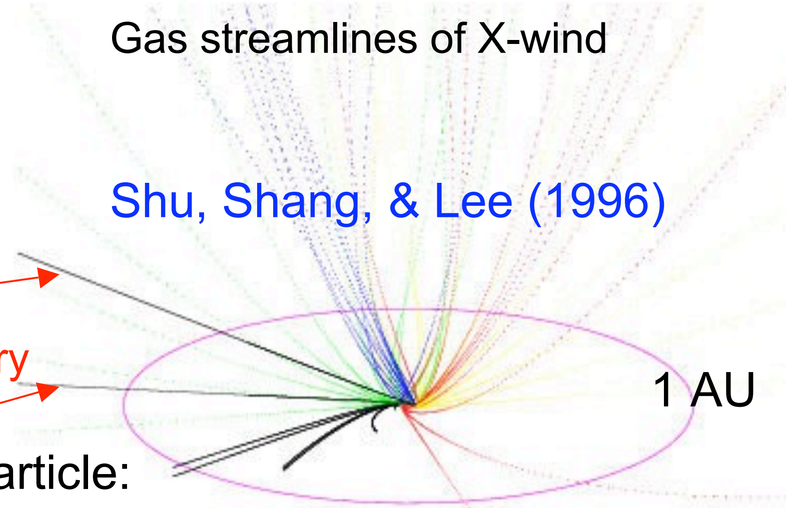
Photo credit: Mike Cai

- As accretion (blue-white) disk tries to spiral into central star, it encounters obstacle of strong stellar magnetic field (purple lines).
- The inwardly extending parts of the magnetic field configuration truncates the disk and forces part the material to flow out of the plane in a funnel (red arrows) onto the star as matter with relatively little angular momentum, explaining why the star ends up round rather than flattened like the disk.
- The other part gains angular momentum from the torques of outwardly extended magnetic field lines and is whipped into a fast outflowing X-wind (green arrows), which collimates eventually into a jet and counter jet flowing in directions parallel and anti-parallel to the rotation axis.

Chondritic Meteorites Are a Mixture of Hot Rock (CAIs & Chondrules Thrown Out in X-wind) and Cold Rock (Matrix Condensed from Disk)



Trajectories of Processed Solids Launched on Median Streamline



Actual trajectory

Projection of trajectory on disk mid-plane

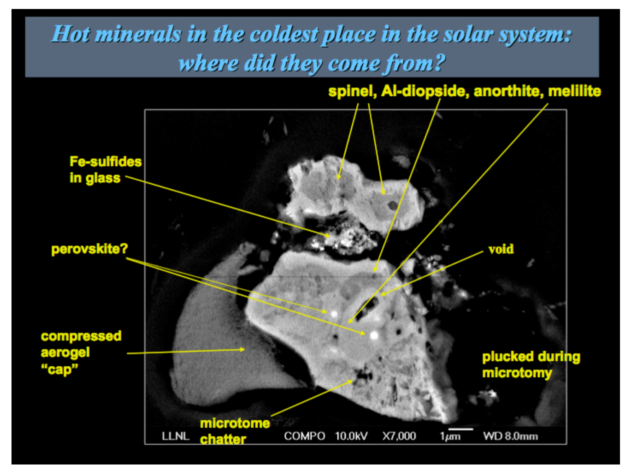
Very small solid particle: thrown to interstellar space

Small: ejected to outer solar system

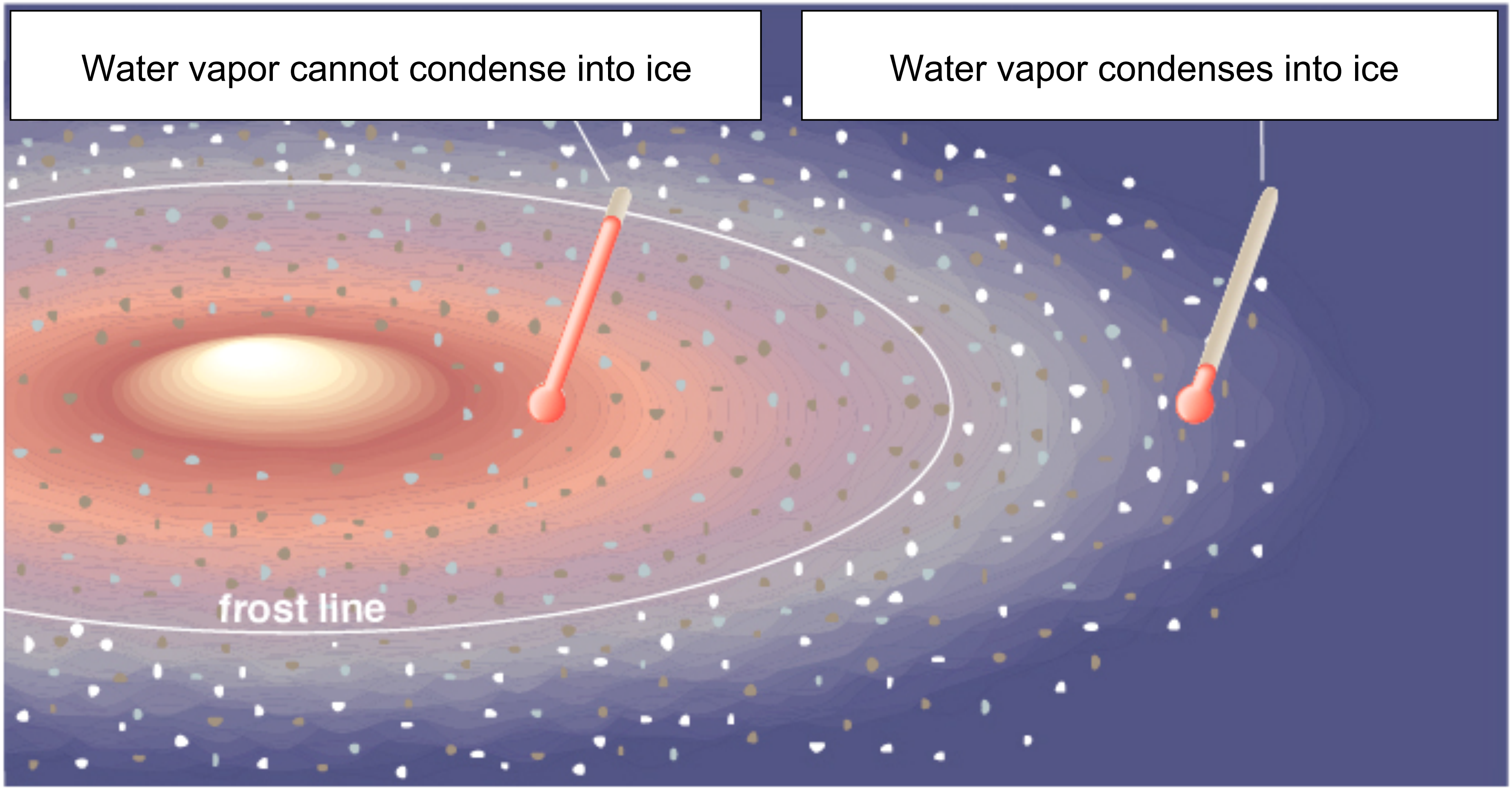
Moderate: ejected to inner solar system

Large: goes back toward Sun

Prediction: CAIs and chondrules should also be found in comets. Borne out by sample of Comet Wild. McKeegan et al. (2006)



Snowline in the Solar Nebula



Temperature is high in inner part of accretion disk and low in outer part. Somewhere inside the orbit of Jupiter, the temperature would have dropped to 100-200 K that would have allowed water vapor to condense to ice at the relatively low pressures of the primitive solar nebula.

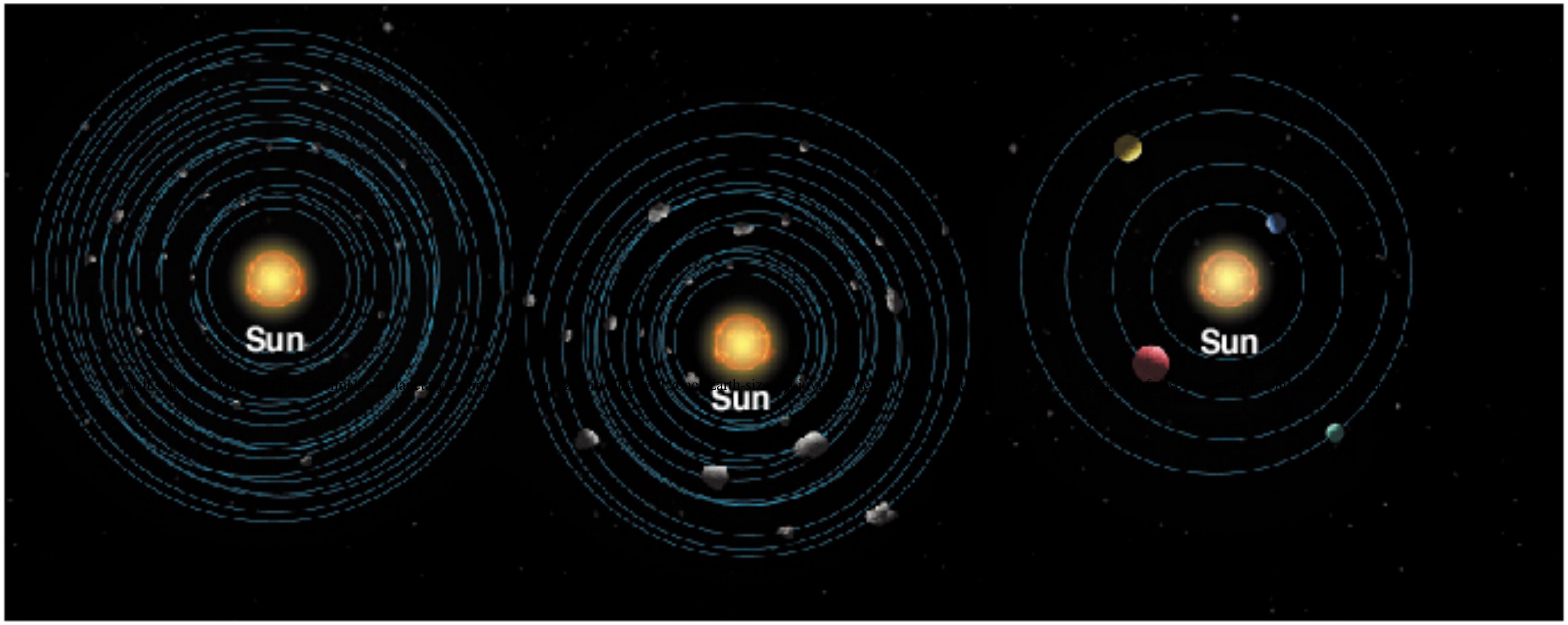
Relative Abundance of Condensates

Materials in the Solar Nebula

	Metals	Rocks	Hydrogen Compounds	Light Gases
				
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	(0.2%)	(0.4%)	(1.4%)	(98%)

Access to water, methane, and ammonia ices can yield larger planetary cores than pure rock and metal objects. Ability to hold onto hydrogen and helium gas can add massive gaseous envelopes.

Agglomeration of Planets



Sticking of small solids or gravitational instability of sub-layer of solids →
km-sized planetesimals → runaway gravitational agglomeration to planetary embryos
(Moon-sized in terrestrial zone; Earth-sized in jovian zone) → dynamical
isolation of individual embryos which leads to slower growth to rocky (and icy in case of giant planets) planetary cores, followed by gravitational accretion of large envelope of gaseous hydrogen and helium in cases of Jupiter & Saturn, followed by gap clearing by Jupiter.

Late Stages of Accumulation of Solids Are Dominated By Large Impacts

Analogy of Gap Opening by Embedded Body

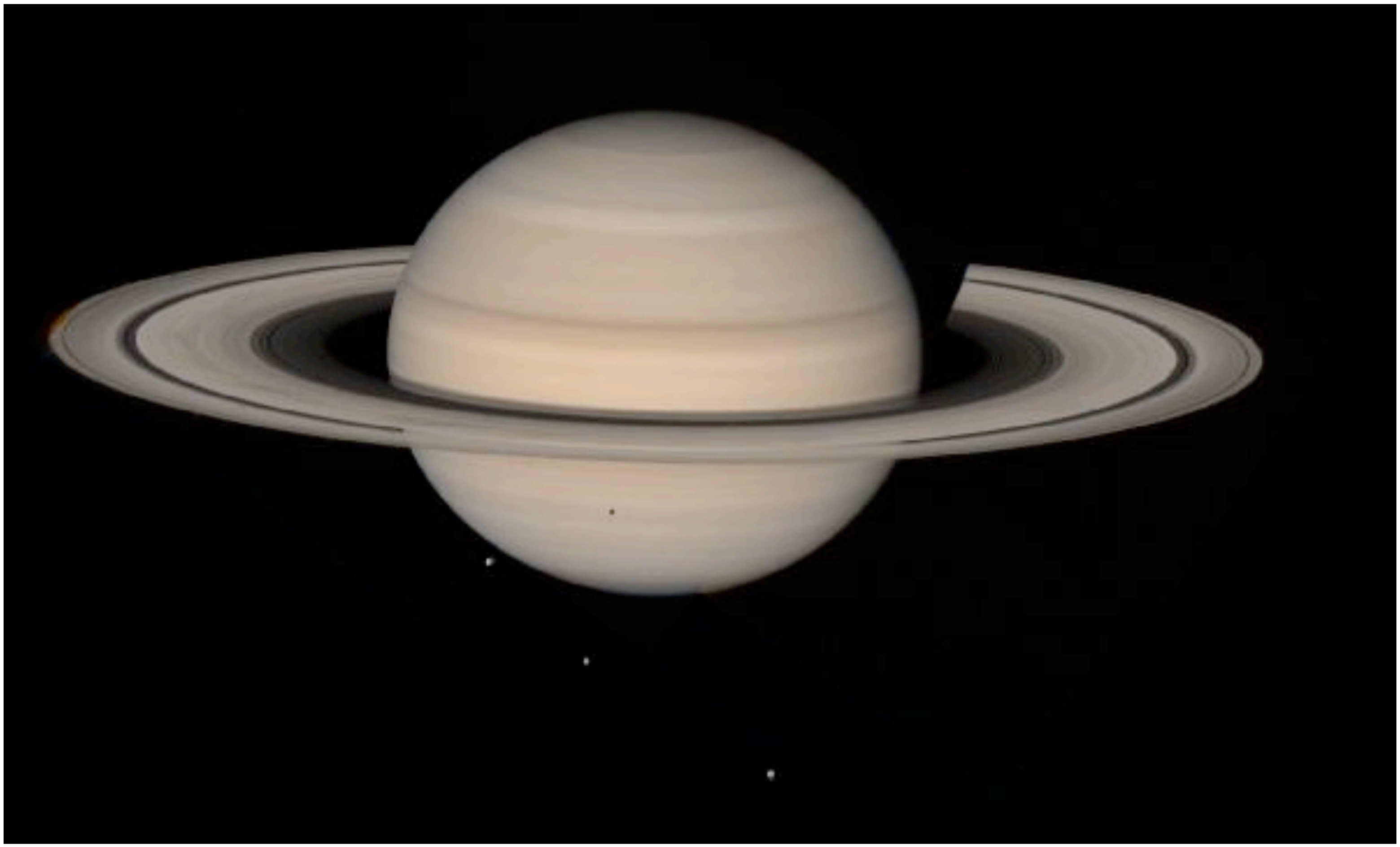
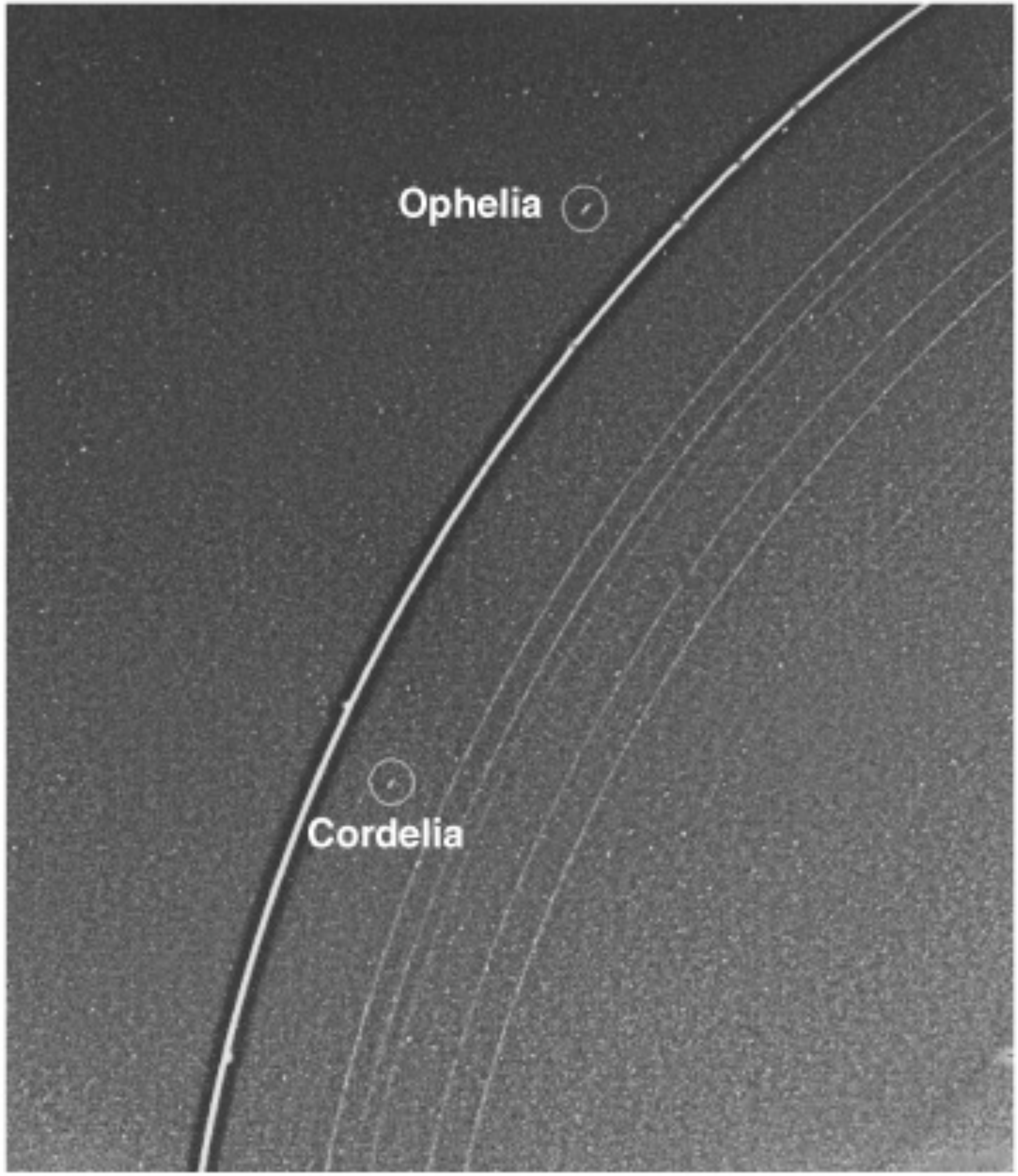


Photo Credit: NASA/JPL

Analogous opening of gap in solar nebula may have stopped growth of Jupiter.

Angular Momentum Transfer to and from Disk Illustrated by Shepherding Satellites in Uranus's Rings

Goldreich & Tremaine (1980)



The Bodies of the Solar System (to Scale)

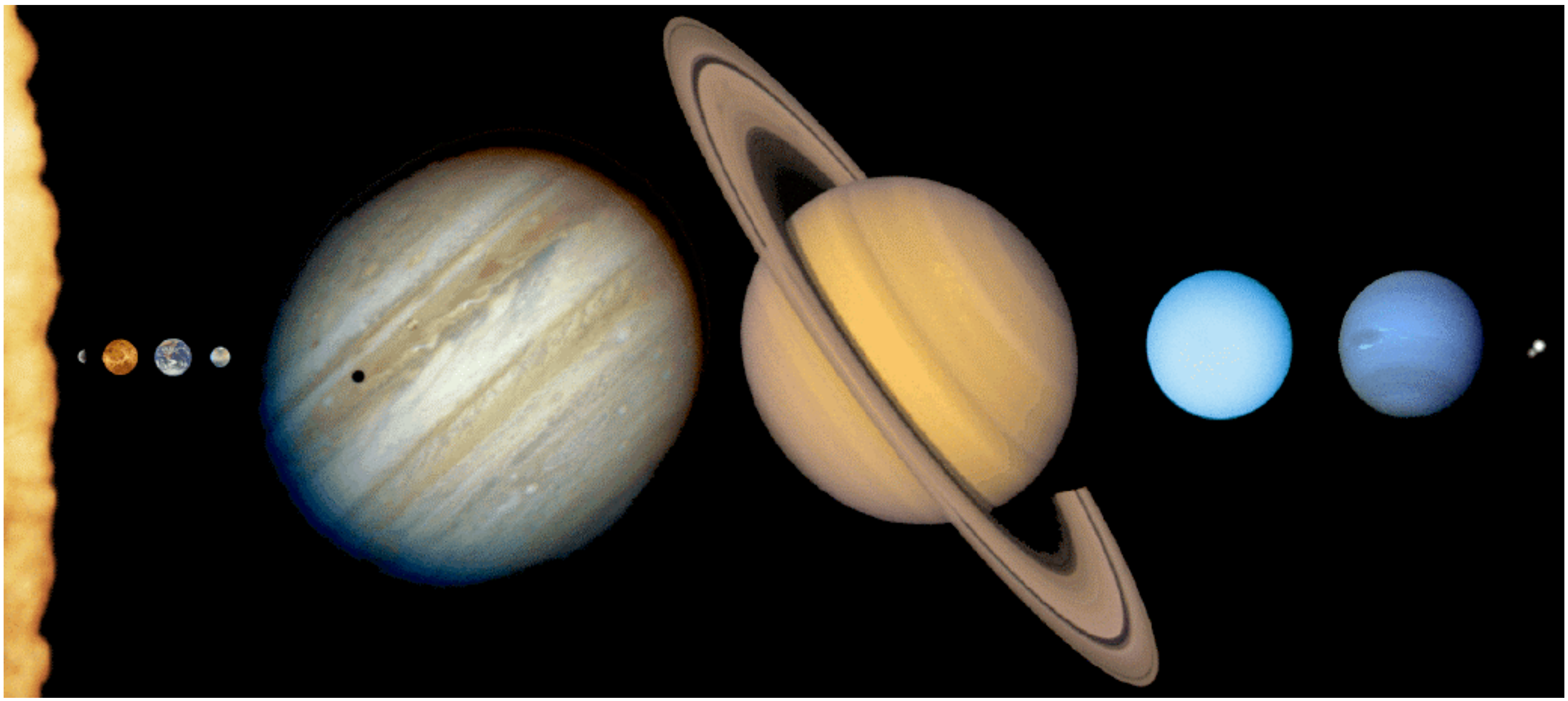
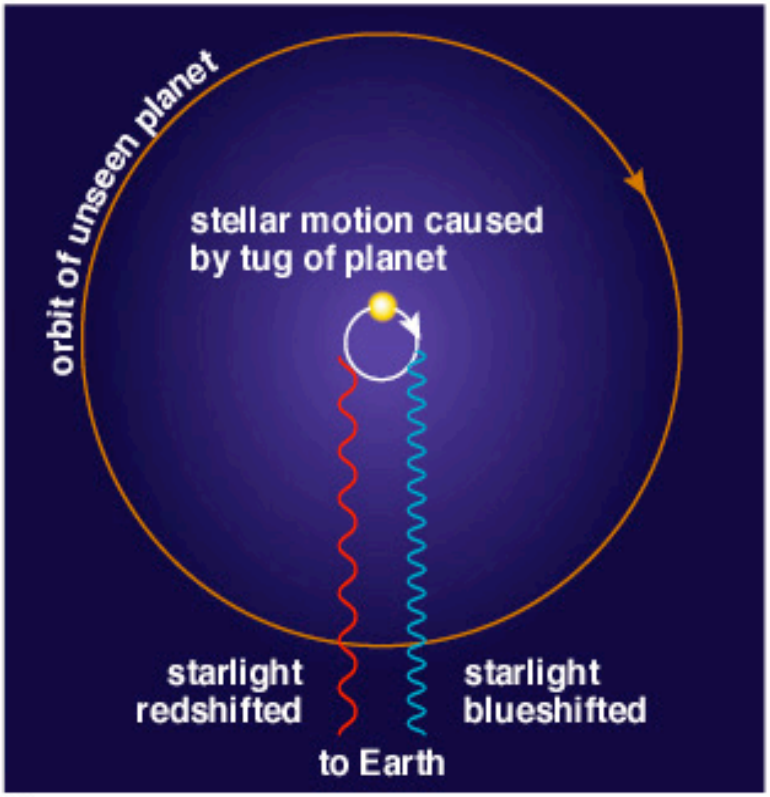
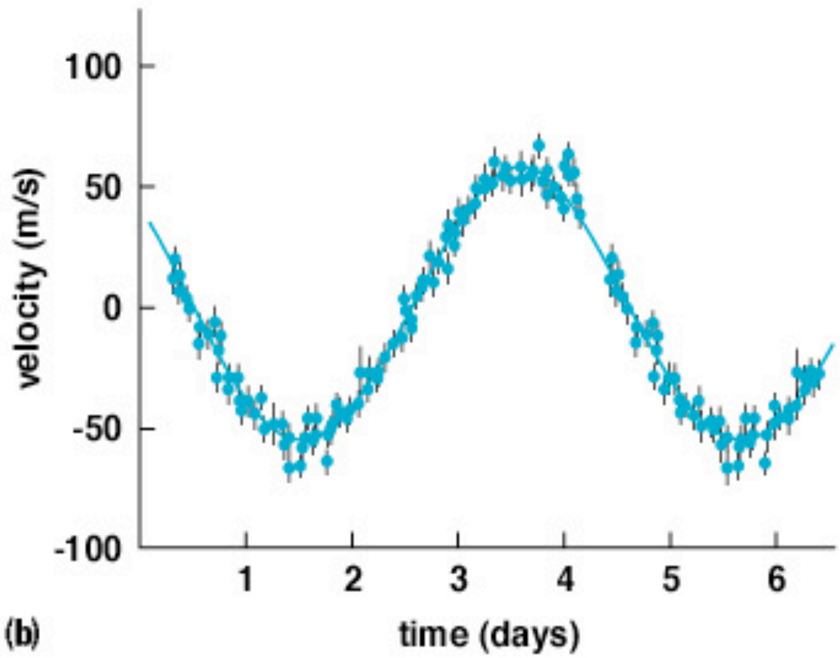


Photo Credit: C. J. Hamilton/NASA/JPL

Extrasolar Planets Detected by Doppler Wobbling of Central Star



(a)



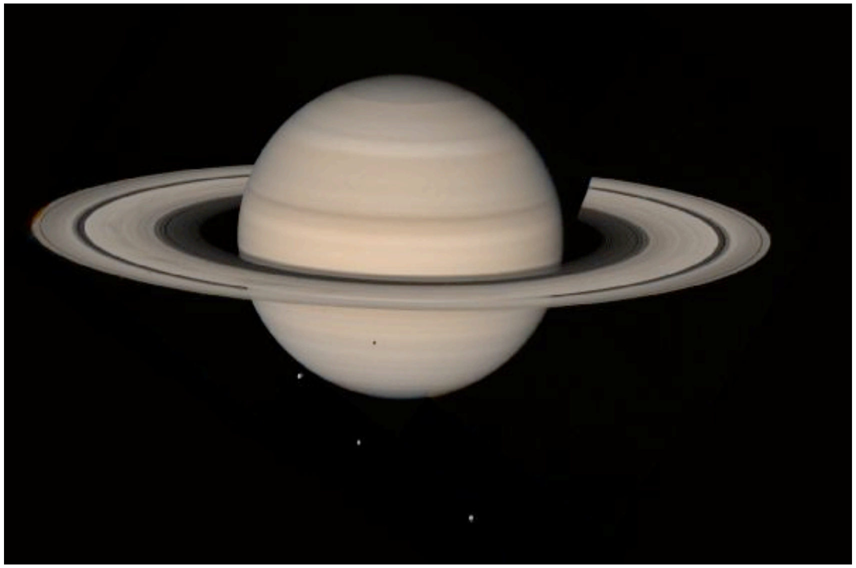
(b)

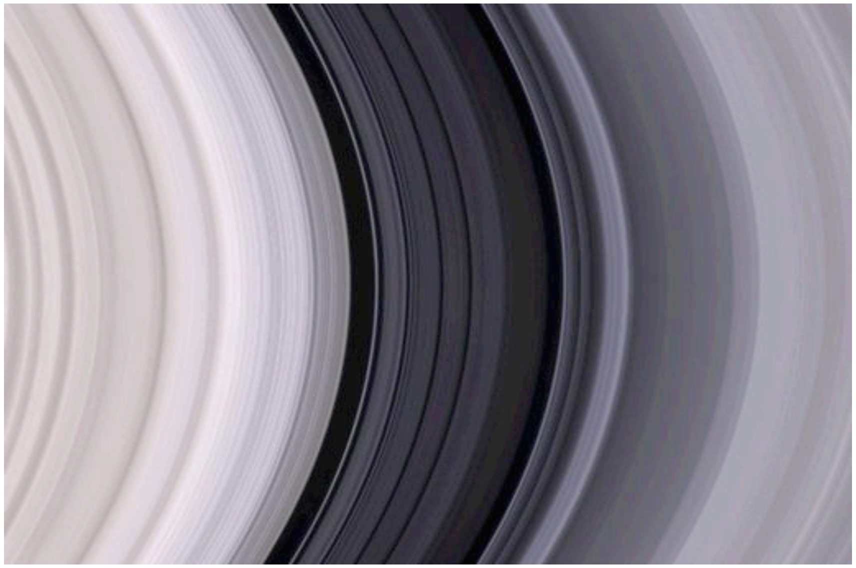
Discovery of 51 Peg by Mayor and Queloz;

Confirmation by Marcy and Butler.

If this giant planet formed beyond snowline of 51 Peg's disk, then it must have migrated inward to a radius ~ 1% of its original one!

Orbit Migration Was Previously Studied in Connection with Dynamics of Rings and Satellites of Giant Planets

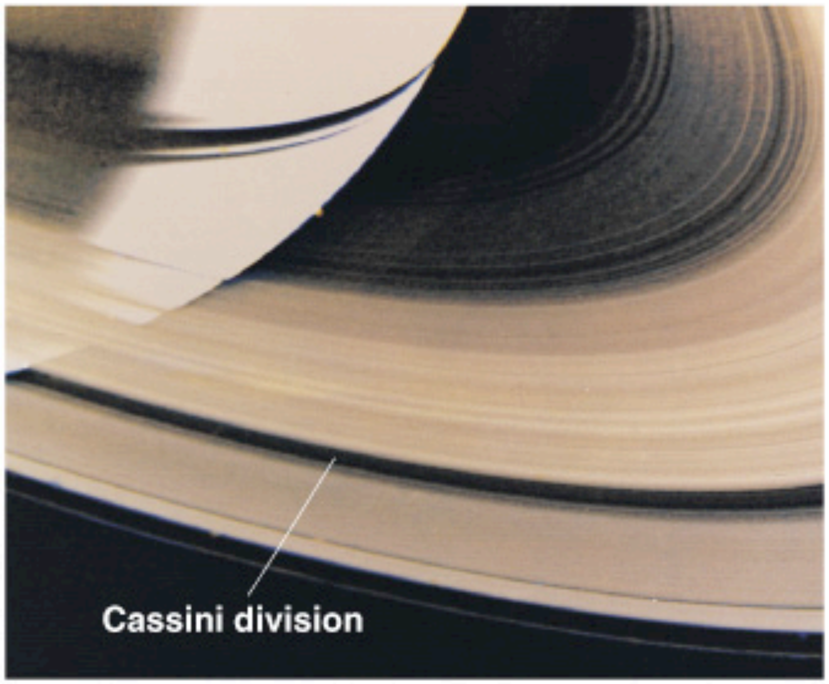




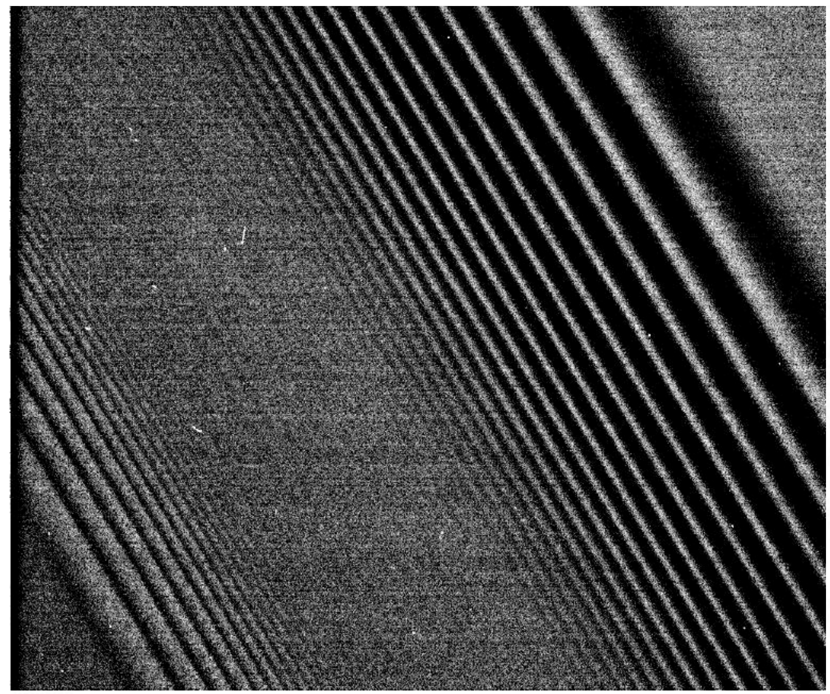
- Voyager 1 imaging team: Is it safe to fly through Cassini Division to check on Goldreich & Tremaine’s theory of how it was cleared through resonant launching of spiral density waves by Mimas.
- “No, not safe,” so plan was fortunately abandoned. When Voyager 1 flew by Saturn, cameras showed Cassini Division contained residual ring particles, striped with mysterious gaps. Explanation: embedded moonlets clearing gaps via mechanism studied by Lin & Papaloizou. Came to realization that back reaction would cause moonlets to move until opposite torques from both sides were equal.
- In other words, gravitational interactions of embedded moonlets with rings (or protoplanets with protostellar disks) could cause their orbits to migrate!

Photo Credit: NASA/JPL

Direct Evidence for Resonant Interactions of Moons with Saturn's A Ring in Finding of Density and Bending Waves



(a)

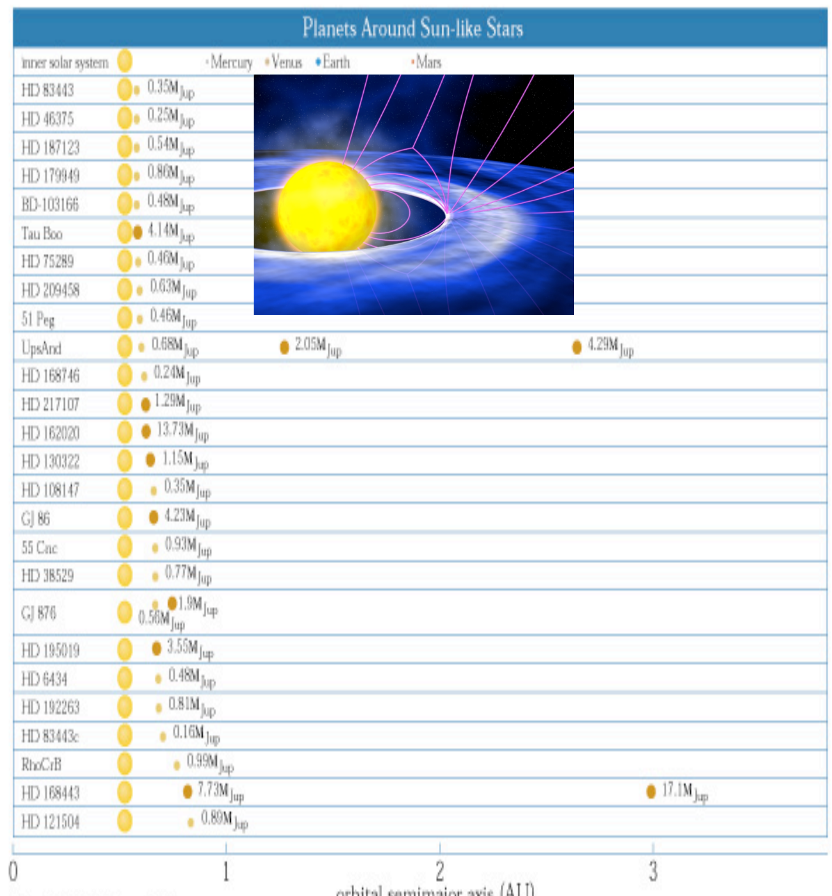


(b)

Shu, Lissauer, & Cuzzi (1983)

Close-In Extrasolar Planets (“Hot Jupiters”)

A possibility: As a giant planet is driven inward by interaction with the part of the disk outside its orbital radius, it eventually spirals past the edge of the inner hole carved out by the disk’s interaction with the stellar magnetosphere. Once the giant planet is so deep inside the hole that its orbital period becomes less than 1/2 of the Kepler rotation period of the inner edge of the disk, the last resonance(1:2) is gone, and the giant planet can safely park within the hole with no further migration induced. This typically gives a final orbital period for “hot Jupiters” of just a few days.



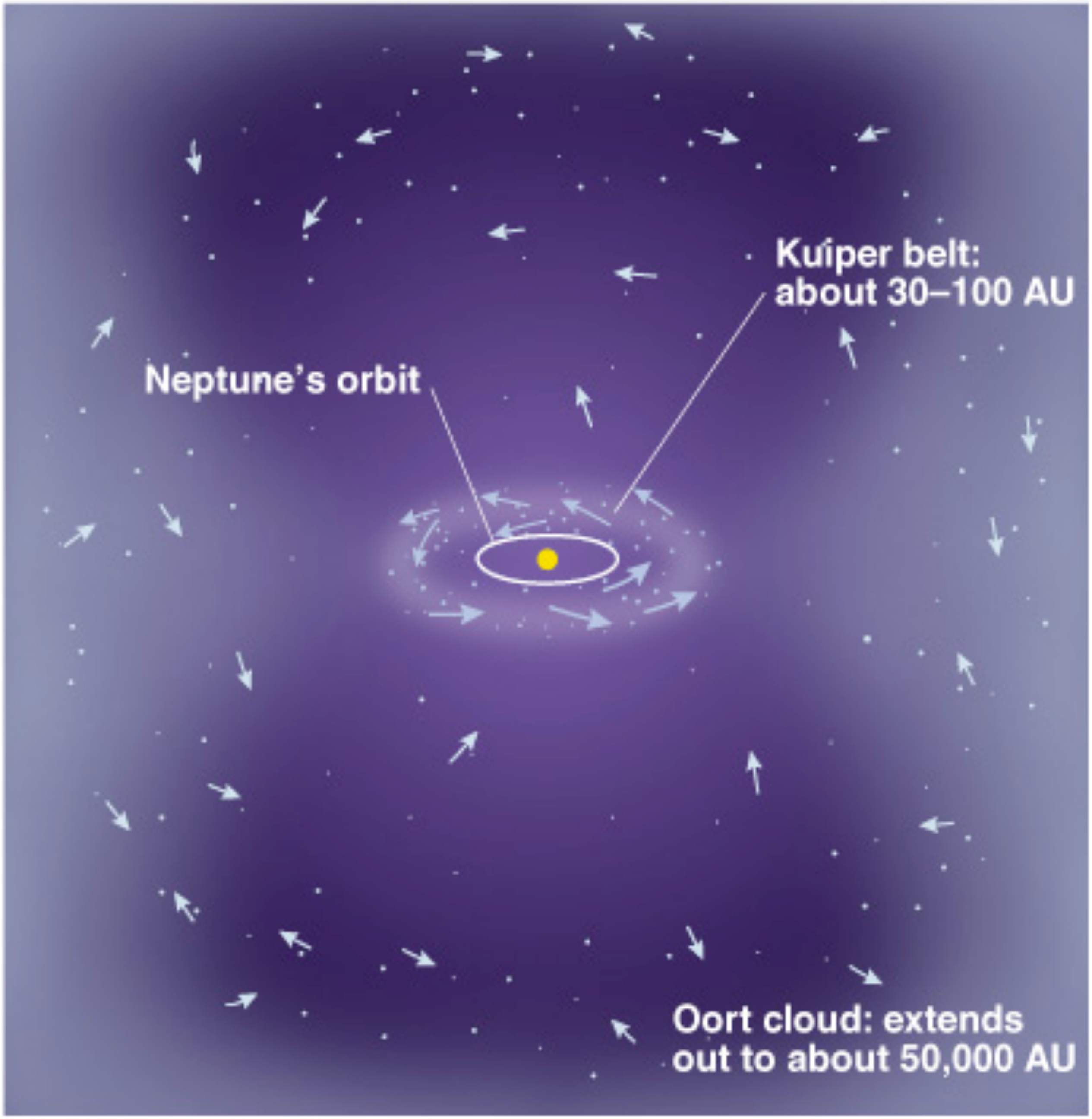
Marcy webpage

Physical Property of Planets in Our Solar System

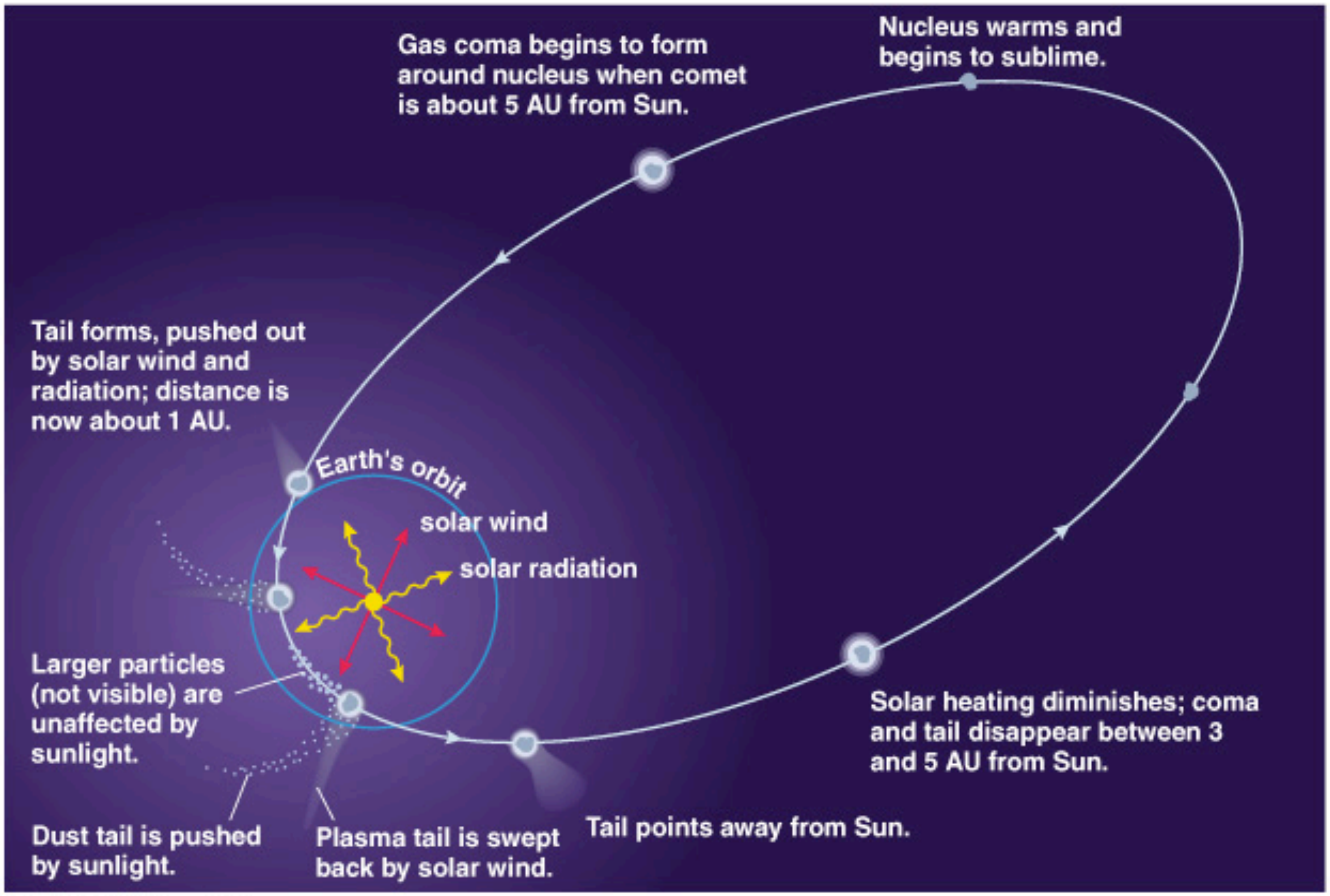
Table 8.2 Comparison of Terrestrial and Jovian Planets

Terrestrial Planets	Jovian Planets
Smaller size and mass	Larger size and mass
Higher density (rocks, metals)	Lower density (light gases, hydrogen compounds)
Solid surface	No solid surface
Closer to the Sun (and closer together)	Farther from the Sun (and farther apart)
Warmer	Cooler
Few (if any) moons and no rings	Rings and many moons

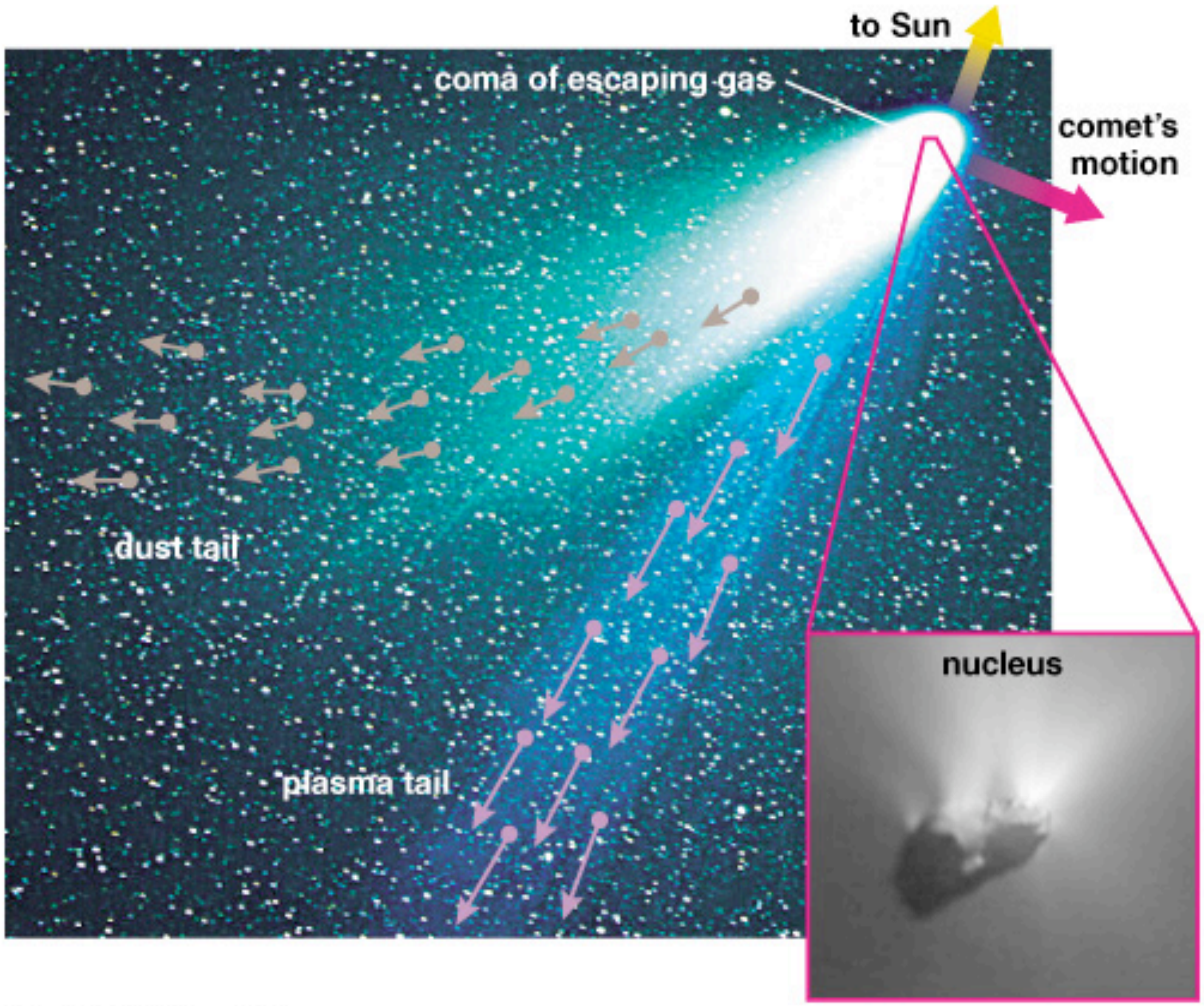
Comets Are Planetesimals of Outer Solar System



Evaporation of Volatiles Leads Comets to Develop Tails if They Penetrate Inner Solar System

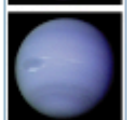
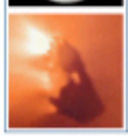


Comets Are "Dirty Snowballs"



Outer Bodies in Solar System

Table 8.1(b) Planetary Facts*

Photo	Planet	Average Distance from Sun (AU)	Temperature†	Relative Size	Average Equatorial Radius (km)	Average Density (g/cm^3)	Composition	Known Moons	Rings?
	Jupiter	5.20	125 K		71,492	1.33	H, He, hydrogen compounds‡	28	Yes
	Saturn	9.53	95 K		60,268	0.70	H, He, hydrogen compounds‡	30	Yes
	Uranus	19.2	60 K		25,559	1.32	H, He, hydrogen compounds‡	21	Yes
	Neptune	30.1	60 K		24,764	1.64	H, He, hydrogen compounds‡	8	Yes
	Pluto	39.5	40 K		1,160	2.0	Ices, rock	1	No
	Most comets	10–50,000	A few K§		A few km?	<1?	Ices, dust	?	No

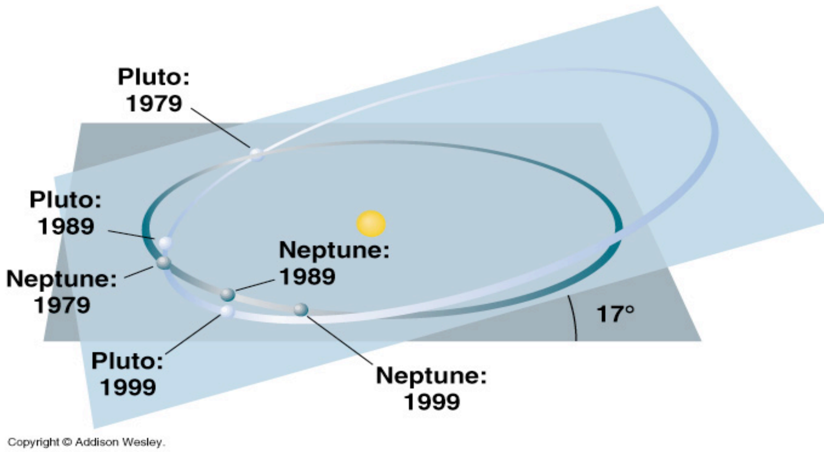
* Appendix C gives a more complete list of planetary properties.

† Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-top temperatures are listed.

‡ Includes water (H_2O), methane (CH_4), and ammonia (NH_3).

§ Comets passing close to the Sun warm considerably, especially their outer layers.

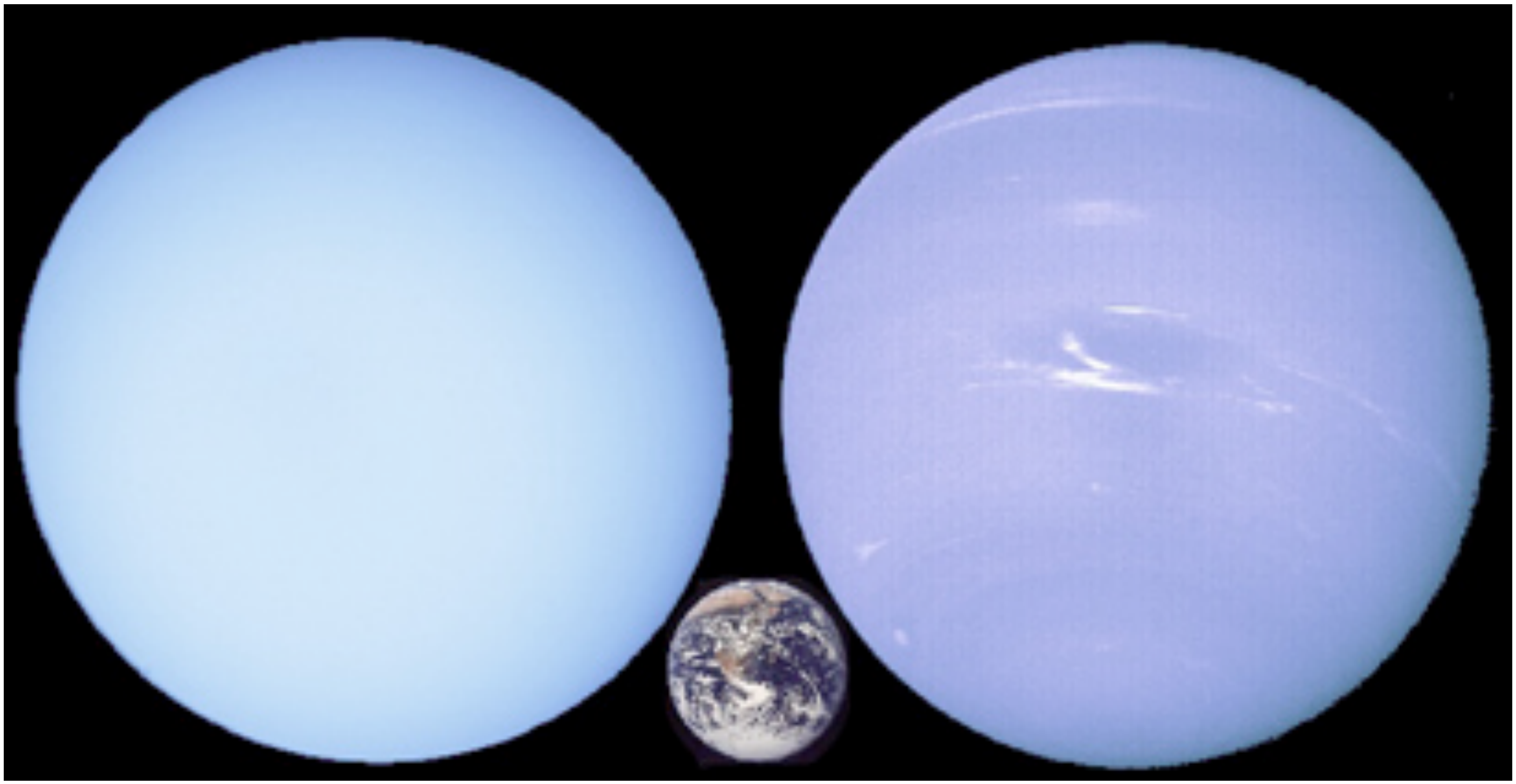
Pluto/Charon Are Accumulations of Billions of Cometary Planetesimals



NASA/HST

- Pluto goes around Sun twice for every three times that Neptune goes around. Their orbits cross, but they won't collide. However, the resonance pumps up the eccentricity of Pluto's orbit.
- Many other "plutinos" share the resonant 2:3 orbit, giving major reason for IAU's downgrading Pluto's status.

Uranus and Neptune Are Accumulations of Trillions of Cometary Planetesimals



Except for surface markings, Uranus and Neptune are virtually twins and much larger in mass and size than the Earth. At their centers, Jupiter and Saturn may have molten rock/ice cores similar to Uranus and Neptune, but they have much more massive hydrogen/helium gas envelopes on top.

Comet Shoemaker-Levy 9 Illustrates How Cores of Giant Planets Accumulated

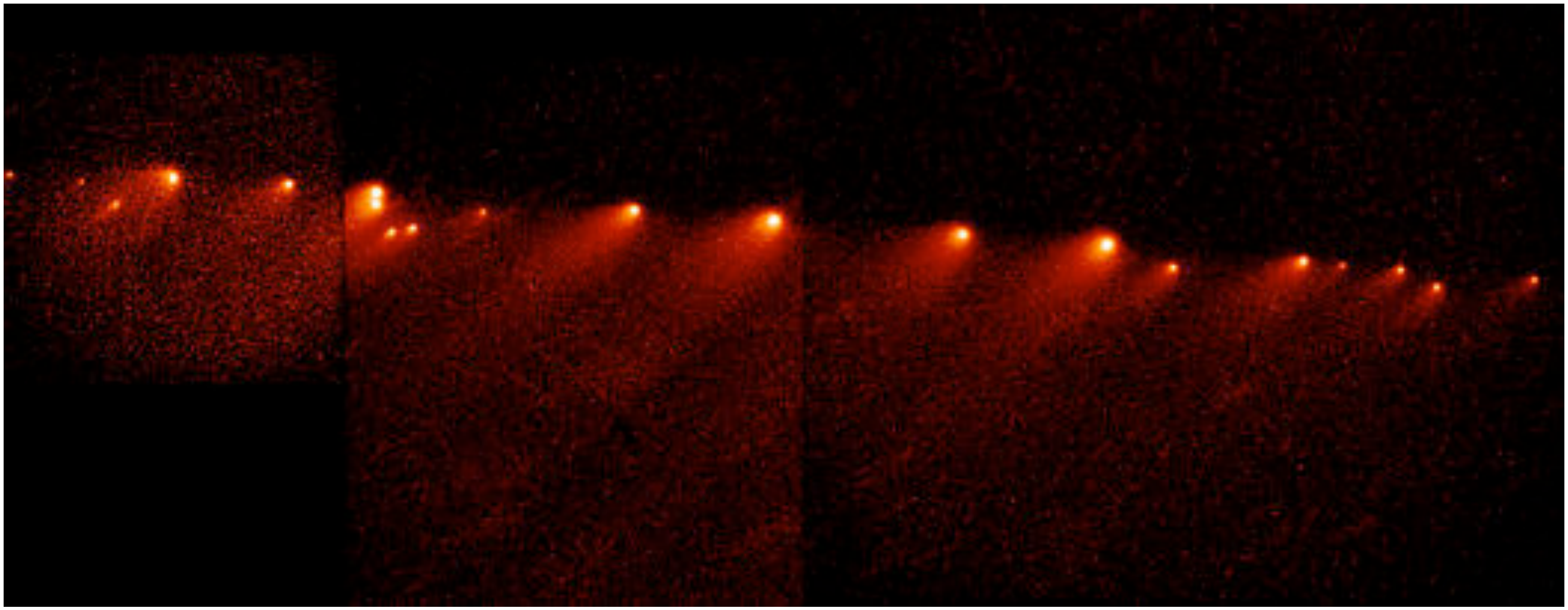


Photo Credit: HST Comet Science Team/NASA

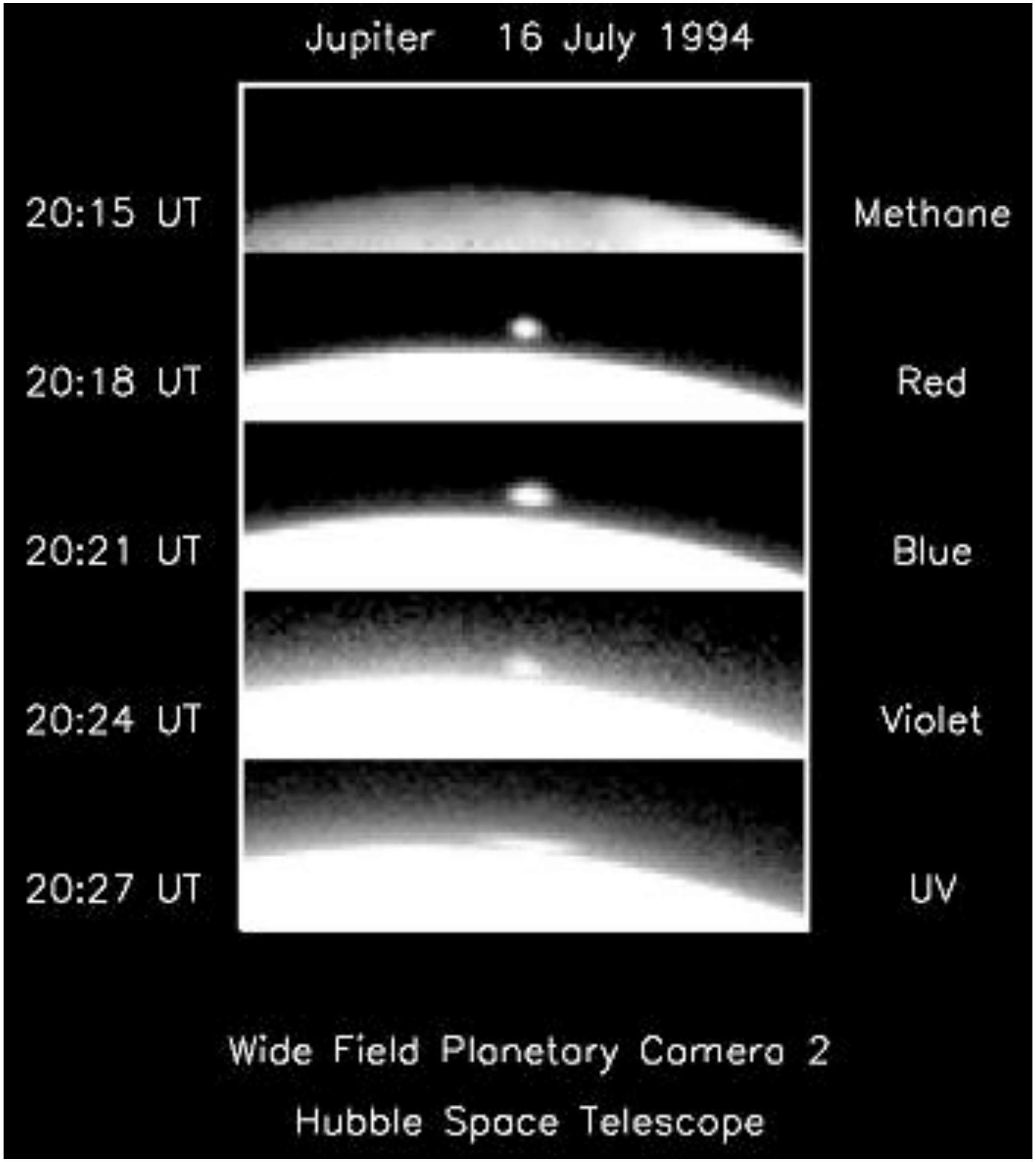
Captured by Jupiter, perturbations due to the Sun caused SL-9 in 1994 to head on a collision course with Jupiter after first being ripped apart by tidal forces into about two dozen pieces.

Photo Credit: STScI/NASA

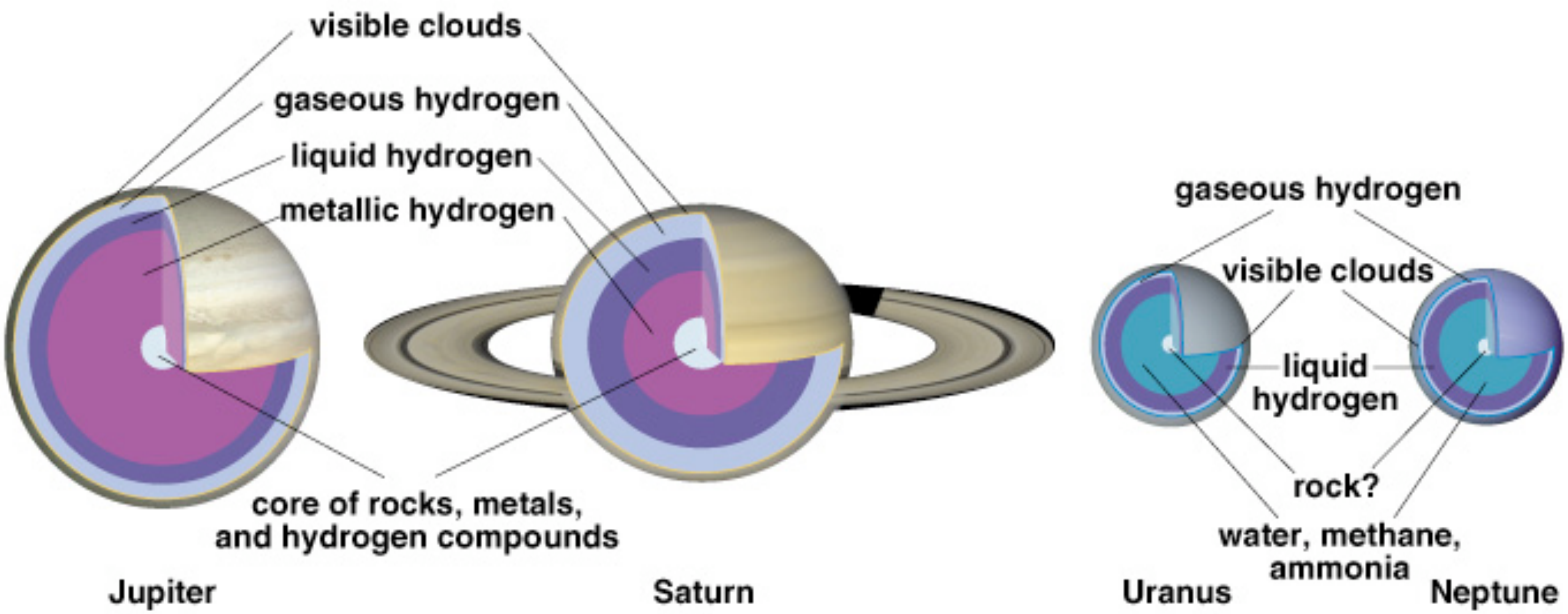
Fireball Caused by Cometary Impact

Entry of SL-9 pieces into Jupiter's atmosphere occurred over the horizon of Jupiter relative to telescopes sited on or orbiting Earth. However, the release of shockwave energy equal to many thermonuclear bombs created an explosion that became visible as the fireball rose above the horizon and then later collapsed and flattened back down.

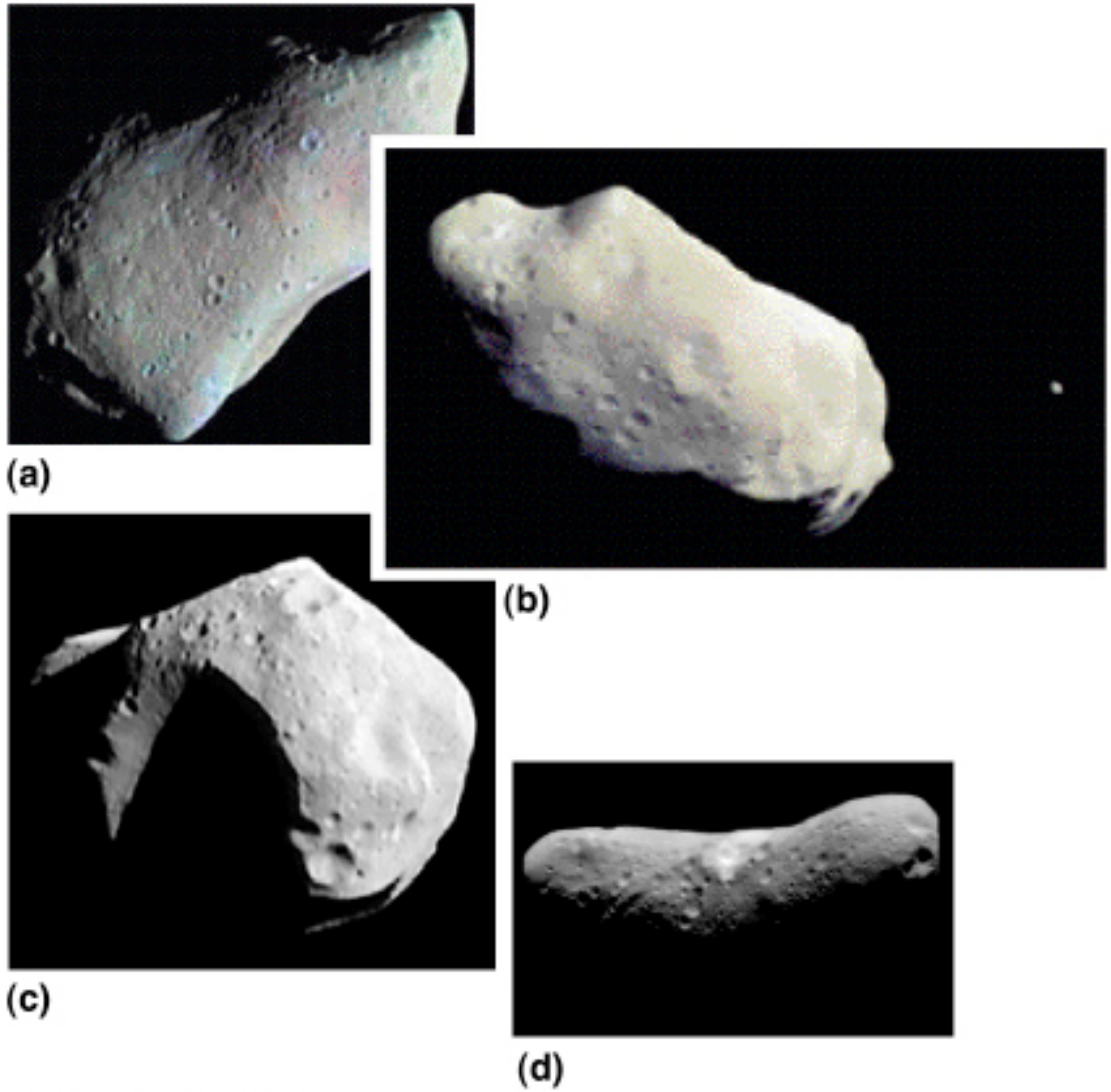
Instead of happening once every several decades, events like SL-9 occurred a thousand times a day when solar system was young.



Interior Structure of Giant Planets

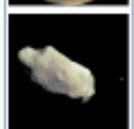


Asteroids Are Planetesimals of Inner Solar System



Inner Bodies in Solar System

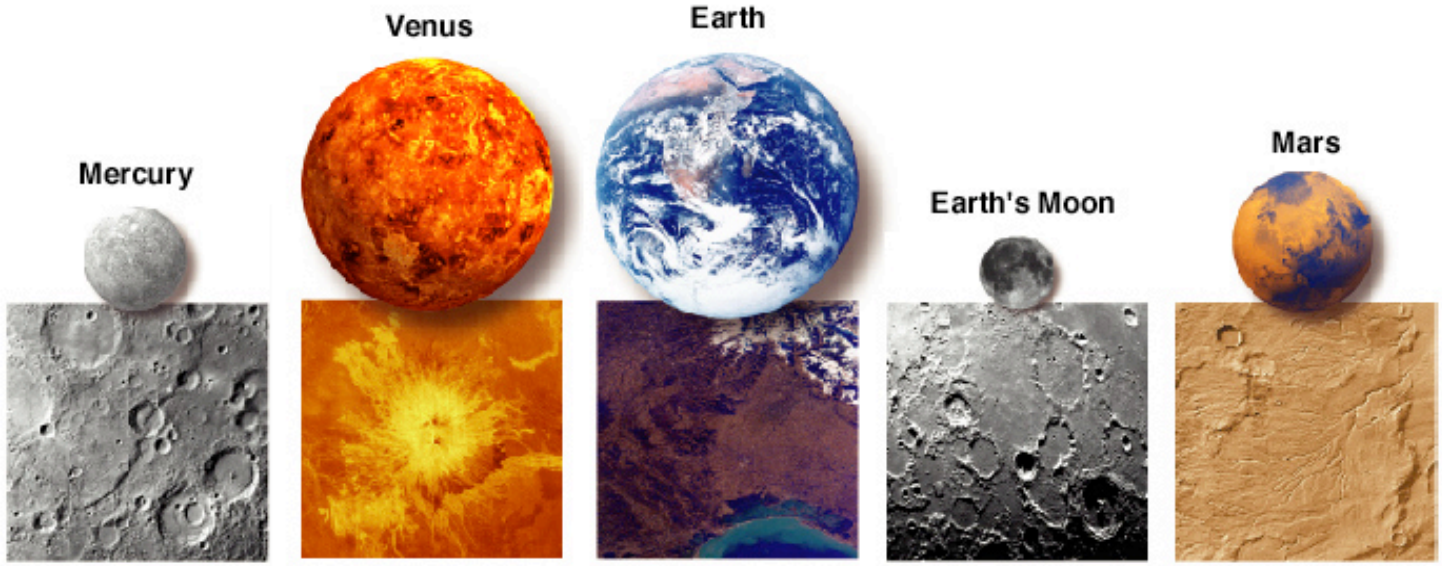
Table 8.1(a) Planetary Facts*

Photo	Planet	Average Distance from Sun (AU)	Temperature†	Relative Size	Average Equatorial Radius (km)	Average Density (g/cm^3)	Composition	Known Moons	Rings?
	Mercury	0.387	700 K	·	2,440	5.43	Rocks, metals	0	No
	Venus	0.723	740 K	•	6,051	5.24	Rocks, metals	0	No
	Earth	1.00	290 K	•	6,378	5.52	Rocks, metals	1	No
	Mars	1.52	240 K	·	3,397	3.93	Rocks, metals	2 (tiny)	No
	Most asteroids	2–3	170 K	·	≤500	1.5–3	Rocks, metals	?	No

* Appendix C gives a more complete list of planetary properties.

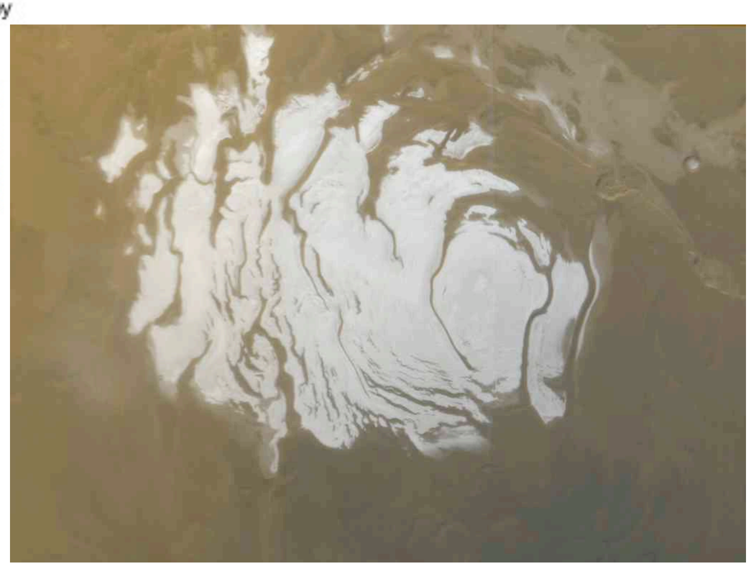
† Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-top temperatures are listed.

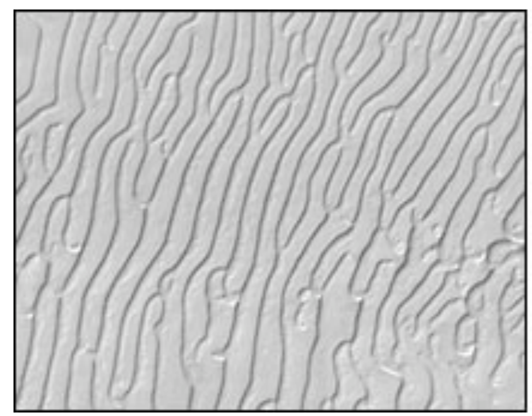
Portrait of Terrestrial Planets



Runaway Greenhouse Effect: Russian spacecraft landings on Venus found surface temperature hot enough to melt lead.

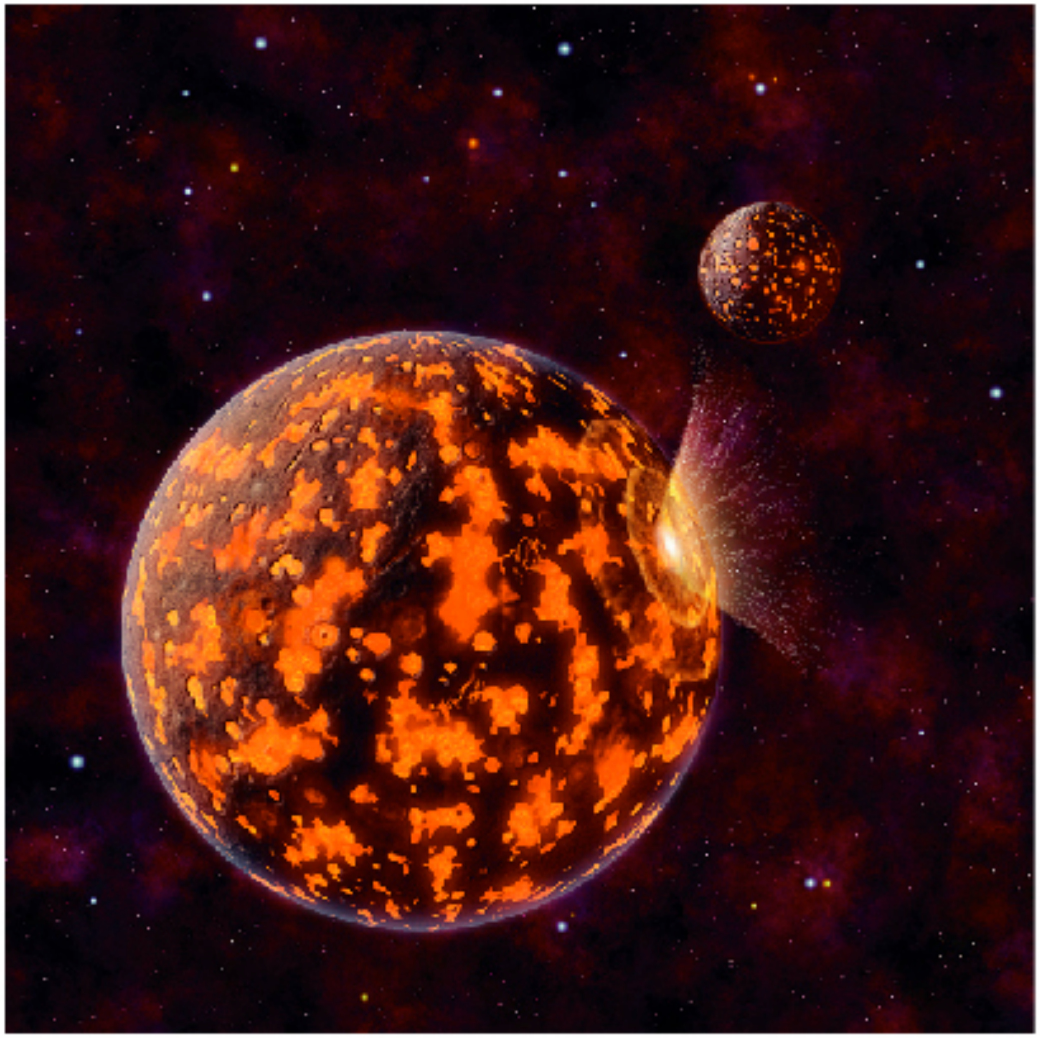
(e) Mars



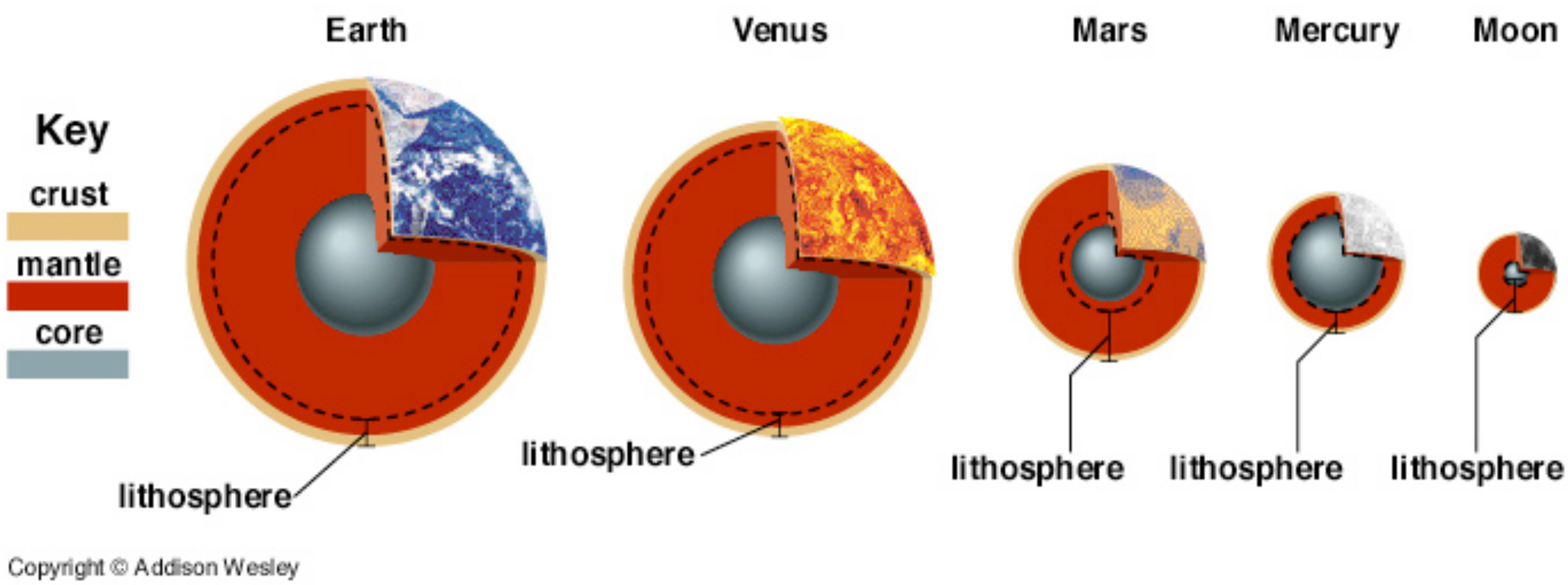


Mars’ south polar cap contains strange water ice formations.

Large Impacts Depositing Heat In Deep Interior May Have Melted Terrestrial Planets

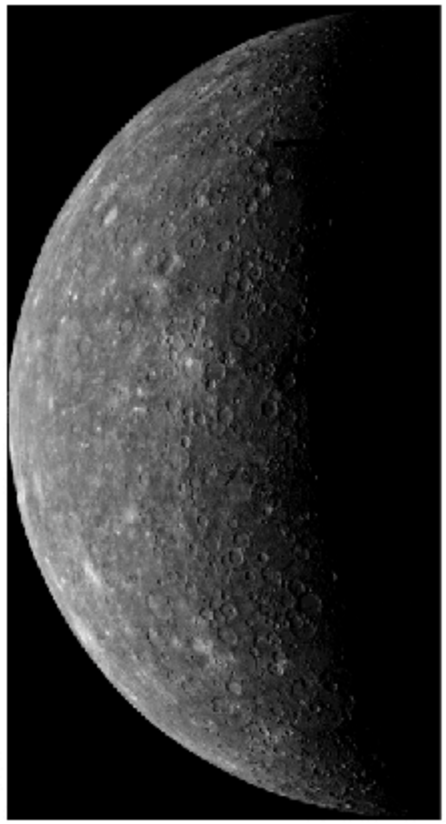


Differentiated Interior Structure of Terrestrial Planets

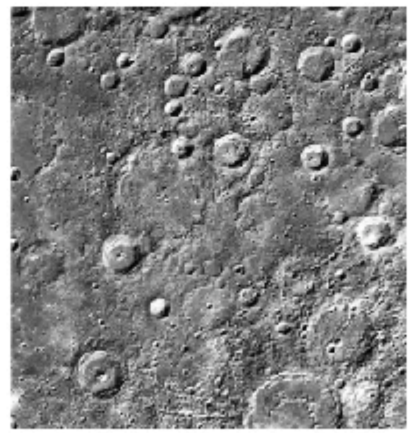


Lacking Much Radioactive Heat Because its Rock Mantle is Thin, Mercury Cooled, Shrank, and Shriveled Up like a Prune

(a) Edge of Caloris Basin

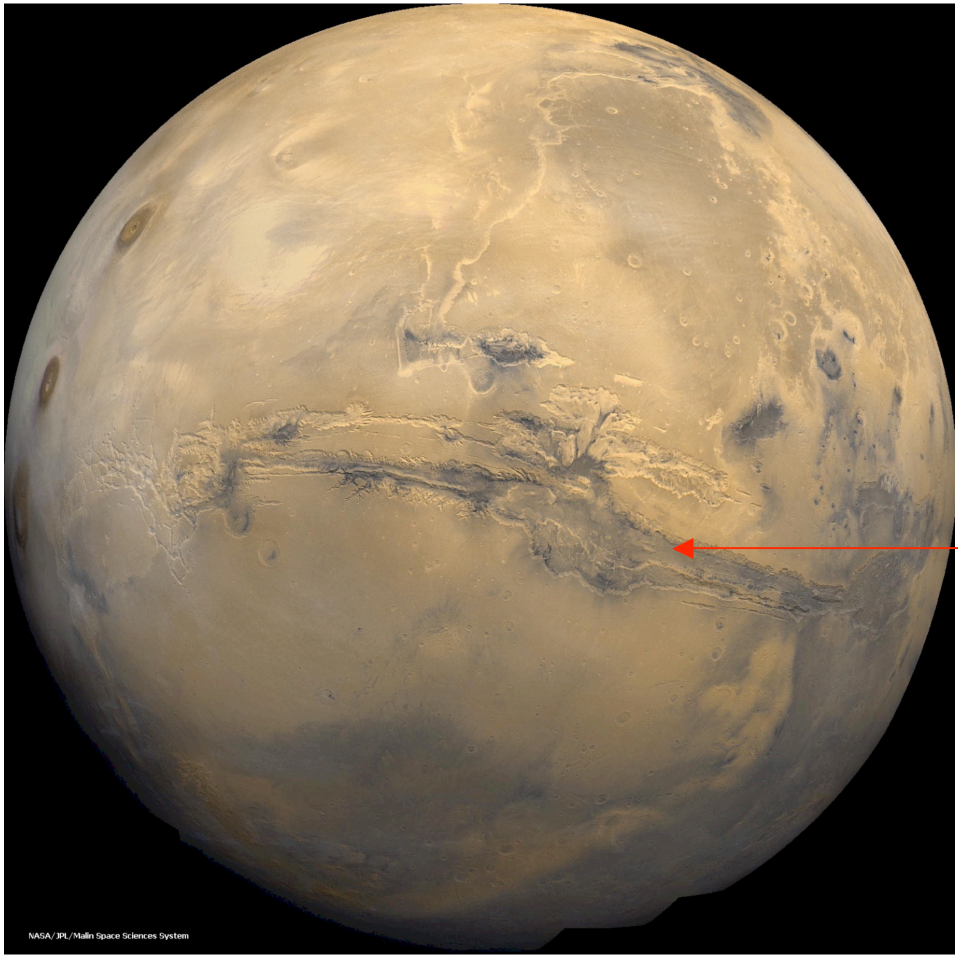


(b) Mercury



(c) Closeup view shows small lava plains that have covered up craters

Heating Up Until Recently from Radioactive Elements Trapped in its Thick Rock Mantle, Mars Expanded and Developed Large Surface Cracks.

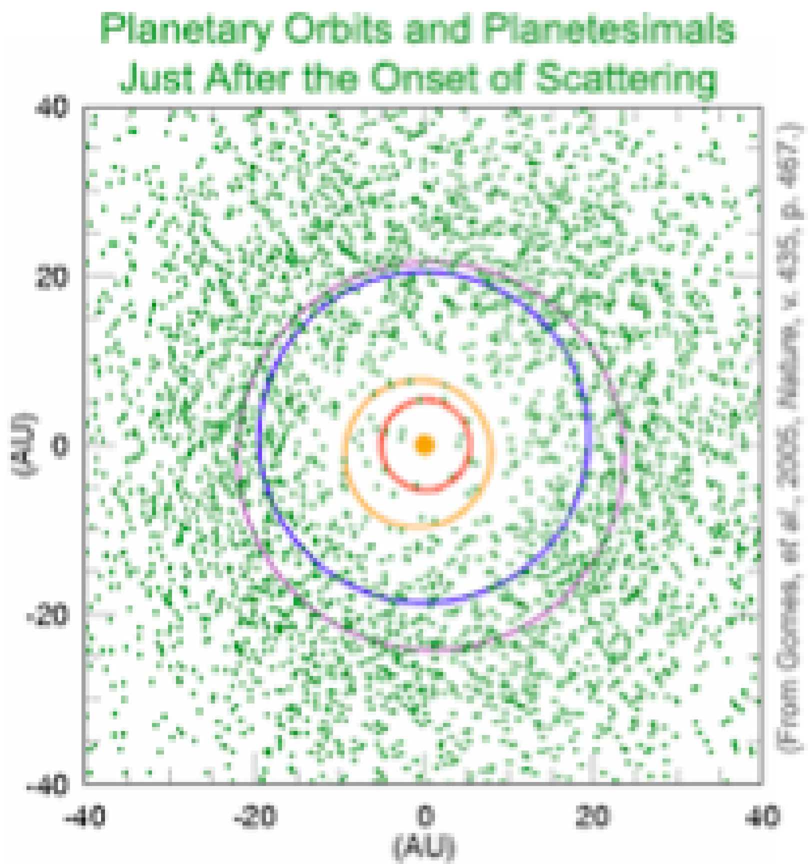


Valles Marineris is much longer and wider than Grand Canyon on Earth.

NASA/JPL

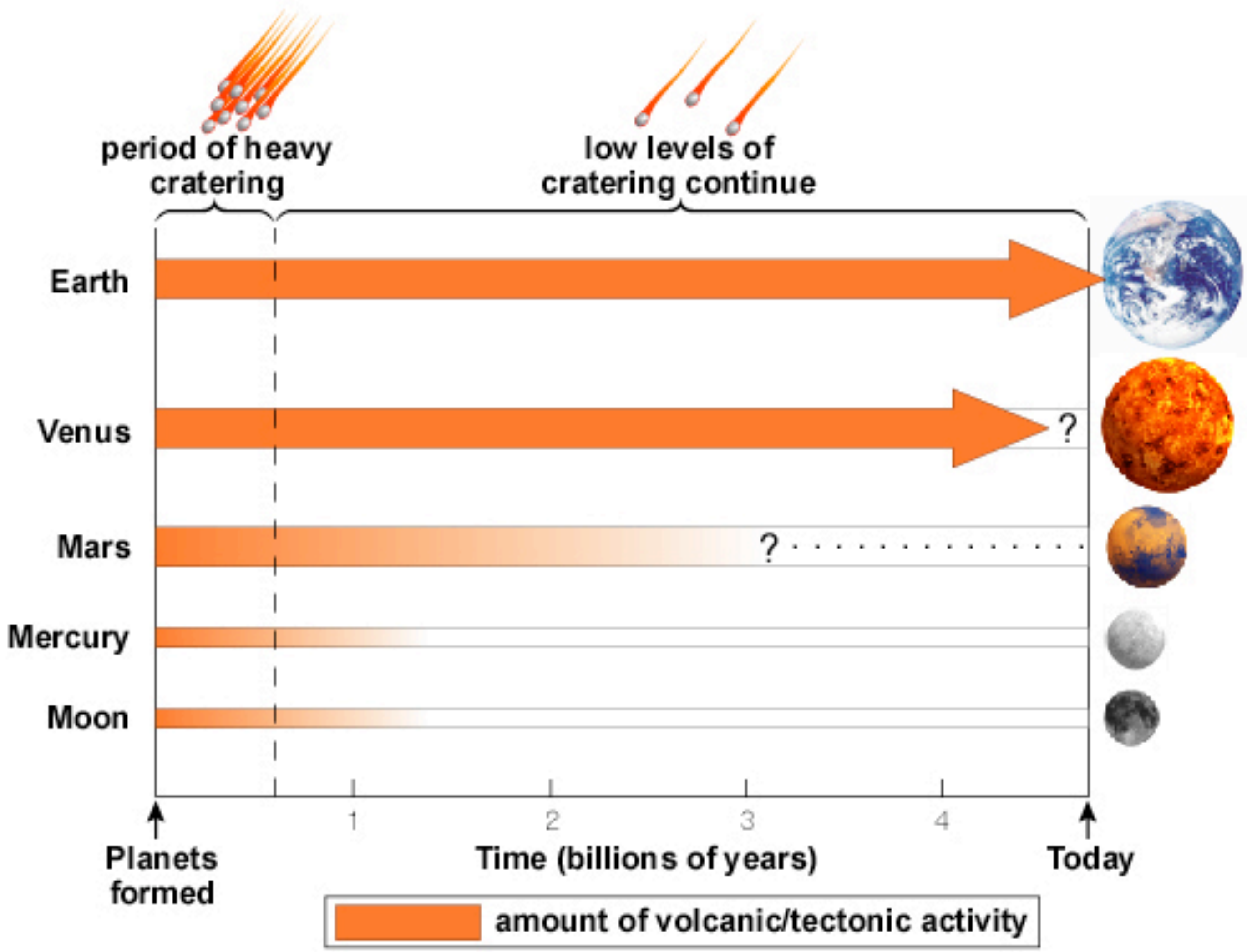
Late Bombardment of Terrestrial Planets May Have Lasted 0.5 GYr

- Orbital migration of Jupiter & Saturn may have caused them to enter 2:1 resonance (ejection of another planet?).
- Effect on planetesimals & Uranus & Neptune may have caused these to migrate outwards to their present locations, locking Pluto & other plutinos into 3:2 resonance with Neptune (a major reason Pluto was demoted from planet status) and scattering planetesimals (comets) into KBOs (Fernandez & Ip 1984) & Oort Cloud.
- Origin of Moon dated to this time?

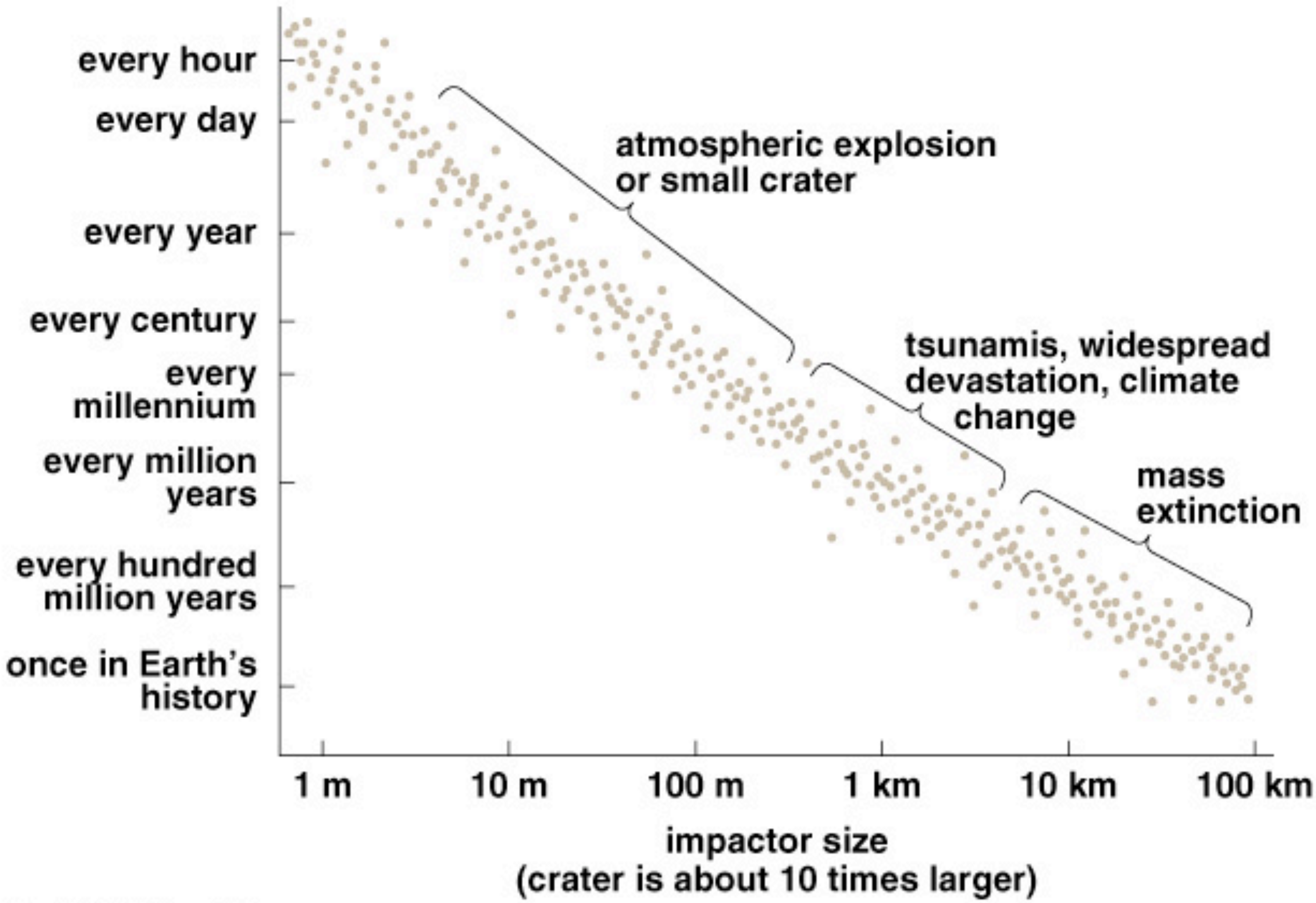


Nice (France) model

Crater Record of Terrestrial Planets



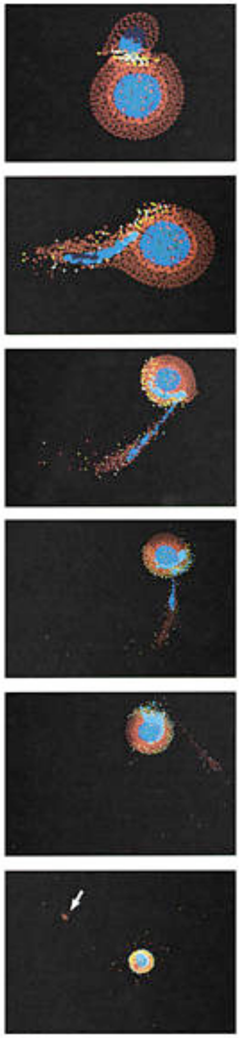
Frequency of Impacts on Earth



Calibration of crater density with radioactive dating of lunar rocks from Apollo sample return.

Large-Impact Origin of the Moon

- Apollo lunar landings found that Moon is deficient in iron compared, say, to the Earth.
- Best explanation is that by Hartmann & Davis and Cameron & Ward: Moon formed from spray of Earth's iron-depleted mantle when a differentiated Earth, whose iron had settled to core, was struck a glancing blow by a Mars-sized embryo.
- Spray went into orbit, and for about a month, the Earth was a spectacularly ringed planet.
- The rocky debris that did not accumulate on Earth eventually agglomerated to form a Moon, with the lunar period then being only about four days.
- Gradually, interaction with the tidal bulges of a faster spinning Earth increased the orbital angular momentum of the Moon (at the expense of the spin angular momentum of the Earth), with the Moon receding today to ~ 60 Earth radii and with the lunar period becoming about a month long.



Giant Impact Killed the Dinosaurs 65 Million Years Ago

Extinction of dinosaurs

Opportunity for mammals

Iridium Layer Laid Down 65 Million Years Ago

Iridium on Earth sank into core along with iron during differentiation of Earth's interior. Iridium brought in by impact laid down a layer, beneath which we find dinosaurs' bones, above which there are no such bones..